THEORETICAL AND PRACTICA ELECTRICAL ENGINEERING

COMPRISING A COURSE OF LECTURES GIVEN AT THE BLISS ELECTRICAL SCHOOL UPON THE PRINCIPLES AND APPLICATIONS OF BOTH DIRECT AND ALTERNATING CURRENT APPARATUS

By

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THEORETICAL AND PRACTICAL ELECTRICAL ENGINEERING

PREFACE

For many years the Bliss Electrical School has felt the need of a single text-book which would treat the fundamental principles underlying the operation of all kinds of electrical devices, in a simple and comprehensive manner, and set forth the practical application of these principles in the engineering world today. But no such book has been found.

Encouraged by the cordial manner in which the many former students of the Bliss Electrical School have received the lectures upon electrical engineering delivered during the past twenty-eight years, and particularly through the urging and hearty co-operation of Mr. Milton M. Flanders, who for the past ten years has been in charge of the Department of Electrical Tests of the Bliss Electrical School, I have ventured to put these lectures into printed form in the belief that they will constitute a text-book of real value for future classes, and with the hope that the Alumni of the School and others generally who are merely interested or actually engaged in the electrical profession, may find the information set forth herein useful.

In connection with this undertaking I wish to make further grateful acknowledgment for the valuable assistance rendered me by members of the Faculty and others.

To Mr. Skipwith P. Coale, who for sixteen years has been closely identified with the theoretical part of the course. His duties have consisted chiefly in reviewing, analyzing and discussing with the student body each and every lecture after it was delivered. He has always advocated the most advanced methods in the conduct of the work. He has contributed considerable technical information and many helpful suggestions in connection with the improvement of the lectures. He has daily read the manuscript of each lecture as it was written, and his constructive criticism of the text has been most valuable.

To Mr. Milton M. Flanders, for his daily reading of the manuscript as each lecture was written, for his clear insight and splen-

did advice as to the accuracy of the technical statements contained therein, and for a considerable amount of additional information which he has contributed to the text.

To Mr. William M. Johnson, Jr., for the painstaking care with which he has produced a large number of the drawings illustrating the text.

To Mr. Mark H. Biser, for his valuable assistance in the preparation of the material on Automobile Ignition and Starting Systems.

To Mr. E. F. Lewis of the Class of 1921, for the faithfulness and endurance with which he daily wrote each lecture as it was dictated, then transcribed it in the rough and finally re-wrote the entire manuscript in its corrected form.

It is only through the cheerful cooperation of all these assistants that the production of this book has been made possible.

Takoma Park, Washington, D. C. LOUIS D. BLISS.
September, 1921.

SECTION I CHAPTER I

STATIC ELECTRICITY

NATURE OF ELECTRICITY

Electricity is an invisible agent through which certain effects may be produced. It is not a source of power. Electricity may best be defined as a **medium for the transmission of power.** It is recognized as a form of energy, but wherever electrical energy appears, an equivalent amount of energy must have been previously supplied in some other form to generate it.

Originally it was supposed that there existed an electrical fluid which pervaded all bodies. When two dissimilar substances were rubbed together it was supposed that an excess of this imaginary electrical fluid was accumulated in one body while the other one was robbed of a portion of its fluid. The one having the excess was said to be positively charged, while the one having less than normal was said to be negatively charged. It is not now believed that there is any such thing as an electrical fluid, at least not in the sense in which it was originally considered.

All space is filled with a weightless gas called ether. This ether is composed of particles so minute that they pass with the utmost freedom through solid substances and also fill interstellar space. The transmission of light and heat from the sun to the earth can only be accounted for on the assumption of the existence of this ether gas. According to this idea the ether is set in vibration by disturbances on the surface of the sun, and waves are propagated in every direction with the incredible velocity of about 189,000 miles per second.

If a stone is thrown into the smooth surface of a pond, minute waves or ripples are projected in every direction through the water. At the seashore waves of greater length may be seen, and in the ocean, during a storm, waves can be observed which are several hundred feet in length from the crest of one to the crest of the next. Thus we see that in water waves of widely different length and magnitude may be produced.

Sound is another illustration of wave motion. Here the waves cannot be seen, but the air, through which sound waves are propagated, is a tangible thing. If a man speaks in a low tone the rate of vibration in the air is low and the length of the

sound waves produced is great. But if a person sings or a musical instrument is played at a high pitch, the rate of vibration of the sound waves in the air is great and the distance from the crest of one to the crest of the next is small. Thus sound waves may be produced of varying length although invisible.

Now the ether is capable of being set in vibration so that waves of different length will result. If the rate of vibration is very great the resulting wave length is very small, and a condition is produced which we call light. Light waves sometimes are no greater than one fifty-thousandth of an inch in length. If, by suitable means, the rate of vibration is made less and the wave length, therefore, longer, the result is a condition which is called heat. Thus while vibrations from the sun reach us, producing the condition of light, there are other vibrations simultaneously transmitted, which produce heat. A blind man sitting in the sun's rays can detect the heat even though he cannot see the light.

If, by certain means, still longer vibrations in the ether are produced, another condition results which is called electricity. Light, heat and electricity are one and the same thing fundamentally. That is, they all consist of vibrations in the ether. The only difference lies in the wave length. They are all projected with the velocity of light, which is, about 189,000 miles per second.

The ancients discovered that when amber was rubbed it developed the property of attracting light bits of chaff. The Greek word for amber is "Elektron." When another substance developed a similar property they said it had the property of amber, that is, the property of "Elektron," or an electrical property. From this word the term "electricity" is derived. It has been used rather loosely and has sometimes been erroneously employed to designate certain things.

When two very dissimilar bodies, such as a hard rubber rod and a woolen cloth are rubbed briskly together, the rod becomes electrified. Moreover it acquires a negative electrical charge. Experiment will further show that the cloth at the same time acquires a positive electrical charge. What is really meant by these expressions is that the friction has caused the ether to be disturbed; a strain has been produced between the surface of the woolen cloth and the rubber rod. What are called opposite

electrical charges are really nothing but the two ends of the same strain in the ether. This fact may be illustrated by a stretched rubber band held in the hands, Fig. 1. It might be said that the hand *A* is charged negatively and the hand *B* is charged

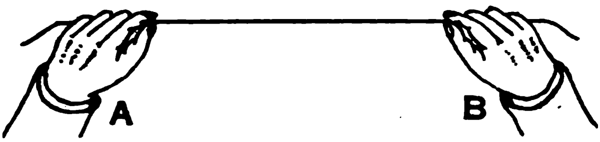


FIG. 1.

positively. What is meant is that the medium, which is the rubber band connecting the two hands, has been strained, and as a result of the strain the two hands are drawn together. A similar condition results when the rubber rod and the woolen cloth are rubbed together. If, now, the two hands holding the rubber band are allowed to approach each other, the strain will disappear.

Lines of electric force emanate from the surface of a positively electrified body. By definition, a line of force is an imaginary line in space along which force acts. The space occupied by these lines is called a **field of force,** or an electro-static field. If a body is isolated in space and is positively electrified, these lines will emanate in a direction always perpendicular to the surface of the body. When two oppositely electrified bodies are placed near one another, lines of force emanate from the surface of the positively electrified body, whence they diverge and then as they approach the negatively electrified body they converge toward it, terminating upon its surface.

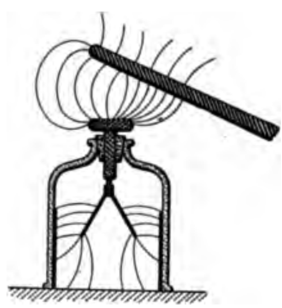


FIG. 2.—Bennett's Gold Leaf electroscope showing action of electrified body on gold leaves.

An **electroscope** is a device for detecting the presence of an electrical charge. The simplest form of electroscope is a wooden needle mounted on a pivot so that it may turn about freely. Also a light feather suspended by a silk thread, or a pith ball suspended in a similar manner, may be employed.

One of the most sensitive electroscopes is that devised by Bennett, Fig. 2. This consists of a glass jar, the mouth of

which is closed by a cork. Through this cork passes a wire to about the center of the jar, where it terminates in a stirrup, in which is hung a piece of gold leaf, extending down on each side, forming two leaves. The upper end of the wire terminates in a brass knob or a button. If an electrified body is approached to this terminal the gold leaves will diverge sharply.

Within the last few years the discovery of radium and other radio-active substances has resulted in the development of a new theory regarding the construction of matter. It has been the custom to call the smallest conceivable particle of substance which could be obtained without losing the identity of the substance a molecule. But the chemist is capable of resolving most molecules by chemical analysis into two or more essentially different substances. These are called atoms. The atom was then regarded as the ultimate particle of matter. Investigation in late years has developed the fact that each atom is composed of minute particles incredibly smaller than the atom. According to this theory every atom is a planetary system on a miniature scale. In the center there is supposed to reside what corresponds to a positive electrical charge or nucleus. Now this charge has never been isolated. Around this positive nucleus are rotating in micro-astronomical orbits, minute particles of matter which, for want of a better name, are called "electrons." The only difference between different kinds of matter is in the number of electrons which the atoms contain. An atom of hydrogen contains a positive nucleus and just one single negative electron rotating around it, even as our moon rotates around the earth. An atom of uranium contains ninety-two electrons in its solar system. There are ninety-two different elementary substances, each differing from the others by one in the number of electrons which it contains.

The electron may then be regarded as a newly discovered form of matter, thousands of times smaller than the hydrogen atom. It carries a negative charge; in fact, all electrons are negative. It has been called an atom of electricity, but electricity is a rather vague term. There is no objection to giving the name "electricity" or "electron" to this newly discovered form of matter, but it does not explain anything. The electron is certainly not electrical quantity nor is it electrical energy, but it is a form of matter which carries electrical energy.

Consider a partially exhausted vacuum tube, Fig. 3, in which are sealed a positive electrode *A*, and a negative electrode *B*, connected to sources of high potential charges. Through the rarefied atmosphere in the glass bulb *C* a luminous discharge will pass from *A* to *B*. Now under certain conditions when a discharge takes place between *A* and *B* there will emanate from the negative electrode *B* a beam of greenish light, which is

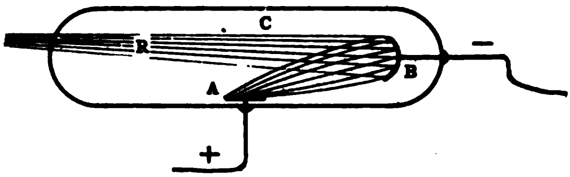


FIG. 3.—Vacuum tube showing cathode ray of radiant matter emanating from negative electrode.

called the cathode ray. This is so termed because the electrode *B* is designated as the cathode of the tube. This cathode ray consists of a stream of radiant matter and is projected with a velocity of about 160,000 miles per second. It consists wholly of electrons. It may not reach or come anywhere near the positive terminal, which may be at one side or even behind the cathode.

Summing up this matter then it may be stated that what is commonly called electricity is a condition resulting from a strain in the ether. It is manifested in vibrations which are propagated through the ether. These vibrations may be directed by means of conductors. By suitable machinery these vibrations may be generated. Well established laws govern the generation, transmission and utilization of this form of energy. The electronic theory simply proposes to explain the construction of matter and the well known laws of attraction and repulsion concerning opposite and similar electrical charges. It is also found to apply to the atomic structure of all other elements which constitute the various known forms of matter.

SECTION I CHAPTER I

STATIC ELECTRICITY

NATURE OF ELECTRICITY

1. Is electricity a source of energy? Is it a natural and inexhaustible source of power?
2. Give two practical definitions of electricity.
3. Explain the one-fluid theory of electricity.
4. Explain the various conditions resulting from vibrations in the ether.
5. Mention some of the early discoveries with reference to friction and the resulting electrical effects.
6. Distinguish between positive and negative electrical charges.
7. Define an electro-static line of force. What constitutes a field of force?
8. Explain the construction and principle of operation of the gold-leaf electroscope.
9. Distinguish between the molecule, the atom and the electron. What is the modern idea of the precise nature of electricity?

STATIC ELECTRICITY

ELECTRO-STATIC INDUCTION

Electrical charges are not known to exist except in or on material bodies. They naturally reside only on the surface of conducting bodies. This may be illustrated by the fact that a hollow metal ball will contain precisely the same charge as a solid metal ball of the same diameter. Faraday constructed a cubical box twelve feet each way, which he covered with tin foil. This he electrified from powerful sources of static electricity. Into this box he carried his most delicate electroscopes, but once inside the electroscopes failed to show the presence of any electrical charge.

If a piece of wool be rubbed on a rubber rod, the rod will acquire a negative charge. If now, the rod is brought in contact with a suspended pith ball, *A*, Fig. 4, it will become charged by

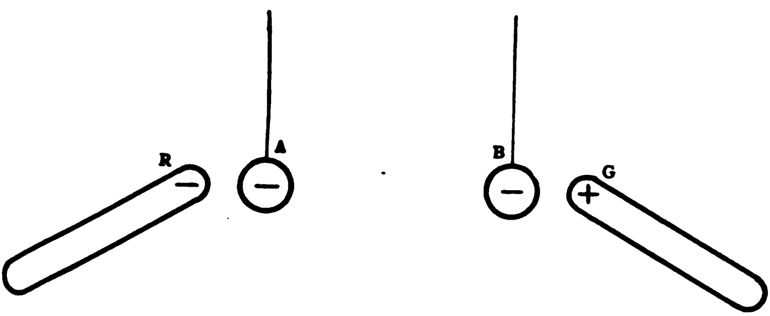


FIG. 4.—Pith balls charged negatively by contact with negatively electrified rubber rod. When *A* is approached by negatively electrified rod *R*, repulsion ensues; when *B* is approached by positively charged rod, *G*, attraction ensues.

conduction. If the rod is brought into contact with another pith ball, *B*, Fig. 4, it also will be negatively charged. If the two pith balls are now approached to each other it will be found that they repel each other. If, now, a glass rod, *G*, is electrified by rubbing it with silk, the glass rod will acquire a positive charge. If such a glass rod be approached to either *A* or *B* attraction will ensue.

These actions illustrate the first law of electro-statics, which is: **"Like charges repel each other; unlike charges attract each other."**

If a hollow brass ball, *A*, Fig. 5, is charged positively, the separate portions of the charge repel each other in accordance with the first law of electro-statics. They will naturally occupy the surface of the body, for they are farther away from each other on the outside than they could possibly be on the inside.

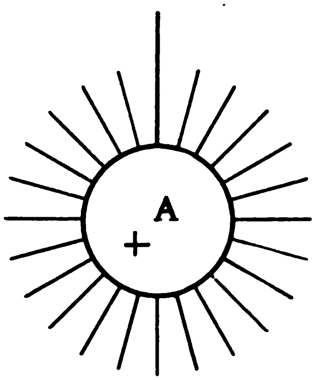


Fig. 5.

If an electrified ball, *A*, Fig. 6, mounted on an insulated support and containing ten positive units, is approached to an uncharged insulated body, *B-C*, the charge on the body *A* will induce a negative charge at the point *B*, and a positive charge at the point *C*. If pith balls be mounted on wires and suspended by cotton threads, as shown, the presence of these charges will be manifested. The ball *D*, electrified by contact with *B*, acquires

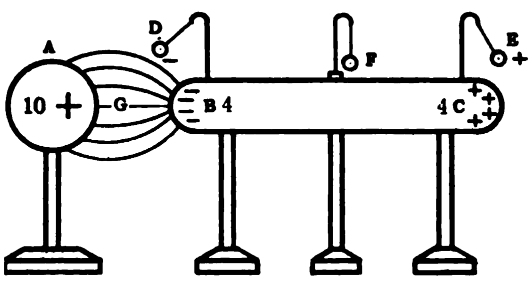


Fig. 6.—Illustration of charges produced by electro-static induction.

a negative charge. It is repelled from *B* and attracted toward *A*, and stands off at some distance. The ball *E*, charged by contact positively, is repelled from *C* a lesser distance because there is no opposite charge in the vicinity to attract it, while the ball *F*, at the center of the body, remains in its original position, indicating the absence of any charge at this point.

This action is known as electro-static induction. It represents the way in which a strain in the ether is transmitted through the intervening air *G*, between *A* and *B*, and reappears again at the point *C*. A similar condition would occur in a cylinder *A*, Fig. 7, in which a piston operating under pressure, communicates through a connecting rod *B*, with another cylinder *C*, filled with

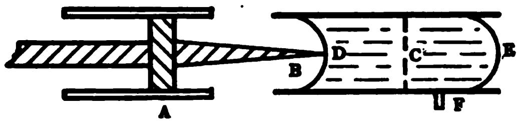


FIG. 7.—Mechanical analogy illustrating negative charge by concave diaphragm and positive charge by convex diaphragm.

water. If the ends of this cylinder were closed with flexible rubber diaphrams, the application of a pressure through *B* would cause the diaphram *D* to be forced inward, and the diaphram *E* to be forced outward. The end of the cylinder which was concave might be said to be negatively charged, while the end *E* which was convex would then represent the positive charge.

The air occupying the space *G*, Fig. 6, between *A* and *B* is called a **"dielectric."** By definition, **a dielectric is any substance which permits induction to take place through its mass.** It must be remembered that a dielectric is not a conductor. In fact all dielectrics are insulators, although the dielectric property and the insulating property of a substance are not directly related. A dielectric is simply a transmitter of a strain. This is represented by the rod *B* in Fig. 7.

If the ball *A*, Fig. 6, is withdrawn from its position, the strain is removed. It is customary to say that the charge at *B* and the charge at *C* are now free to attract each other and flow together, thus neutralizing each other. Equilibrium is thus restored. The body then reverts to its original uncharged condition. This would be equivalent in Fig. 7 to removing the cylinder *A* and the rod *B*, in which case the diaphrams *D* and *E* would again straighten out.

If in Fig. 6 air filled the space *G* while the ball *A* was acting upon *B-C*, there might be induced as much as four negative units at *B* and four positive units at *C*. The amount of induced

negative charge at B will always be exactly equal to the induced charge at C, but both will be less than the charge on A. If a slab of glass is interposed at G the amount of charge induced would be increased. Thus there might be five units induced at B and five at C. If the glass plate were replaced by a slab of mica, there might be six or seven units induced at B and an equal number at C. This is because glass is a better dielectric than air, and mica still better than glass. This quality is referred to as the **dielectric power** of a substance. A slab of shellac would permit a very small amount of induction to take place across it, although shellac is an excellent insulator. Mica is an excellent insulator and also a fine dielectric. This varying ability of different substances to transmit the electrical strain might be illustrated by supposing that the rod B in Fig. 7 was a very slender wooden stick which would bend and thus not readily transmit the strain from A to B, while if it were replaced by a stout steel rod a much greater strain could be transmitted.

Suppose that while the body B-C is under the influence of A it is separated into two parts as in Fig. 8. Now if the inducing body A is removed, the negative charge on B cannot neutralize

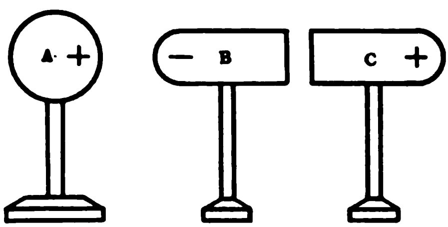


FIG. 8.—Showing isolation of two induced charges if separated while under induction.

with the positive charge on C, because of the insulated space. The two charges thus remain separated until they are gradually dissipated through the air.

It was early found that the presence of moisture greatly facilitated the escape of an electrical charge. The particles of moisture and dust in the atmosphere come in contact with a charged body and acquire some of the charge which it contains. Repulsion then ensues and the particles are violently thrown off. Thousands of these particles are thus constantly engaged in dissipating the original charge which the body possessed.

In the next place suppose that the charged body *A* is brought into the vicinity of the uncharged body *B-C*, Fig. 6, and induction results as before. The charge which is attracted to the point *B* is called the "**bound**" charge. The charge which is repelled to the point *C* is called the "**free**" charge. The latter is repelled as far away as it can get. If now the body under induction is touched by the hand the repelled free charge will escape into the earth. The **earth** is regarded as a **common reservoir** toward which all charges naturally gravitate just as water naturally seeks the ocean level. A similar condition might be obtained in the illustration given in Fig. 7. If a pipe were attached to the cylinder *C* at the point *F* and the pipe connected to an open tank, the diaphram *E* would immediately straighten itself, while the diaphram *D* would remain under tension due to the strain transmitted through *B*. So in Fig. 9 the presence of *A* maintains the strain across the dielectric, and the negative charge which is thus bound remains at *B*, while the positive

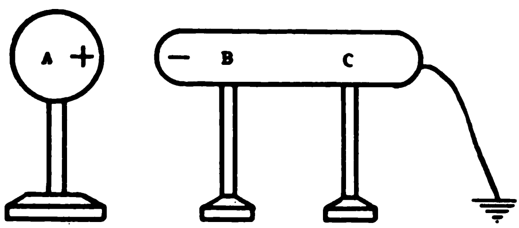


FIG. 9.—Showing how an earth-connected body under induction acquires a charge opposite in sign to that possessed by the inducing body.

charge at *C* disappears. If now the hand is removed and the charged ball *A* is taken away, the body *B-C* is found to retain a negative charge. Thus if an insulated body be touched while under the influence of a charged body it will acquire a charge of opposite sign to that possessed by the inducing body.

The way in which an electrified rubber rod comes to attract a bit of tissue paper or chaff can now be understood. Let a rod, *A*, Fig. 10, which has been negatively charged by rubbing it with a piece of fur, be approached to a table on which there rests a bit of tissue paper, *B*. The charge acts inductively upon the paper, inducing a positive charge at the point nearest the rod and repelling a negative charge to the point farthest away.

The positive charge is attracted by the rod and the negative charge is repelled, but because the positive charge is nearer to the rod than the negative, the attraction is greater than the

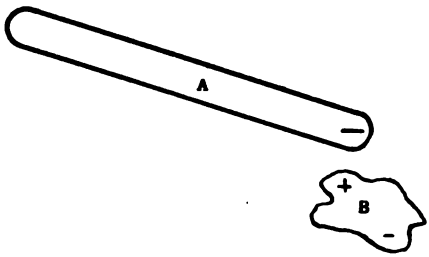


FIG. 10.

repulsion, and the bit of paper flies up to the rod. As soon as the paper comes in contact therewith, the positive charge on the paper neutralizes some of the negative charge in its vicinity on the rod. This requires a few seconds because of the poor conductivity of the paper and the surface of the rod. When, however, it has taken place, the paper *B* possesses only a negative charge, which is repelled by the negative charge on *A* and the paper is violently shot away from the rod.

The gold leaf electroscope may be similarly charged by induction, Fig. 11. Let the negatively charged rod *A* be brought

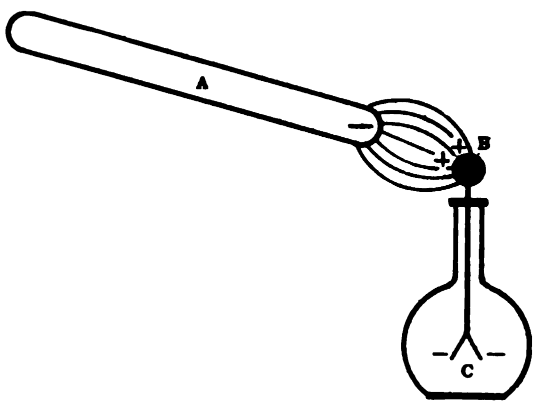


FIG. 11.—Showing Gold Leaf electroscope charged by electro-static induction.

in the vicinity of the knob *B*. Induction ensues and a positive bound charge is attracted to the top of the knob, while an

equal free negative charge is repelled into the gold leaves at C, which are thereby caused to repel each other and they diverge. If now the rod is removed, the charge at B and the charge at C neutralize each other and the leaves collapse. But if while A is in the vicinity of B, the knob is touched by the hand, the free charge at C escapes into the earth and the gold leaves collapse. If now the hand is withdrawn and afterwards the rod A is removed, the positive charge which was held bound in the knob at B is released and distributes itself from B to C and the leaves again diverge, this time with a positive charge instead of a negative.

There are two exceptions to the general rule that charges reside upon the surface of bodies. One is where an insulated charged body is introduced into the interior of another body. The charged body will induce and bind an opposite charge on the inside of the body under induction. The charge will only remain there, however, so long as the inducing charge is present. The other exception is found in the case of electric currents, which occupy the entire cross-section of a conductor instead of traveling on the surface.

The second law of electro-statics is:

The force exerted between two electrified bodies varies directly as the product of the separate charges and inversely as the square of the distance between them.

$$f=\frac{c \times c'}{d^2}$$

f = force in dynes.
c = charge on one body in electro-static units of quantity.
c' = charge on other body in electro-static units of quantity.
d = distance in centimeters between two bodies.

By definition, a unit quantity of electricity is that quantity which, when placed at a distance of one centimeter in air from a similar and equal quantity, will repel it with a force of one dyne.

For example, suppose two electrified balls suspended by silk thread four centimeters apart; one possesses twenty-four units of positive charge and the other eight units of negative charge. Fig. 12. In accordance with the first law of electro-statics they will attract one another. According to the second law, the force

of attraction will equal the product of these charges, 24 times 8 equals 192, divided by the square of the distance between them, 4^2, which equals 12 dynes. If these two balls are brought in contact with each other for a moment there will be a partial

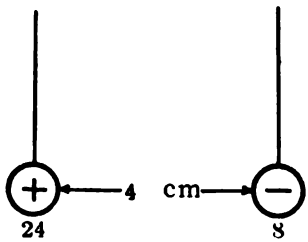


FIG. 12.—Showing attraction between oppositely electrified bodies.

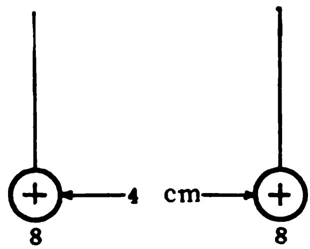


FIG. 13.—Showing redistribution of charges after contact and subsequent repulsion.

neutralization and redistribution of the charges. The eight units of negative charge will unite with and neutralize eight units of positive charge. The remaining sixteen units of positive charge will redistribute themselves equally upon both balls, provided the balls are of the same diameter. If now the balls are removed to their former position, four centimeters apart, Fig. 13, according to the first law of electro-statics they will repel each other because their charges are now both positive. The force of repulsion now manifested according to the second law of electro-statics will be equal to the product of the separate charges, 8 times 8 equals 64, divided by the square of the distance between them, 4^2, equals 4 dynes of repulsion.

SECTION I | CHAPTER II

STATIC ELECTRICITY

ELECTRO-STATIC INDUCTION

1. State the first law of electro-statics.
2. Give a proof that charges reside only on the surface of material bodies.
3. Explain electro-static induction, giving the three steps in the experiment of bringing an insulated uncharged body under the influence of a charged body.
4. Define a dielectric. Mention a few.
5. Distinguish between "free" and "bound" electrical charges.
6. Explain the process by which an electrified body attracts an unelectrified body which is brought into its vicinity.

7. Explain the method of charging an electroscope by induction.

8. What exceptions are there, if any, to the general rule that electrical charges reside upon the surface of bodies?

9. State the second law of electro-statics.

10. If a ball containing 25 positive units is suspended in space 5 centimeters away from another ball charged with 5 negative units, what will be the force in dynes between them? Will it be attraction or repulsion?

11. If a ball containing 58 positive units is brought in contact with a ball containing 18 negative units and they are then moved 10 centimeters apart, what will be the force manifested between them? Will it be attraction or repulsion?

STATIC ELECTRICITY

CONDUCTORS AND INSULATORS

In 1729 Gray found that cotton thread would conduct electricity while silk would not. He succeeded in conducting static charges by this means several hundred feet, the conductor being held up by insulating loops of silk.

No sharp dividing line can be made between conductors and insulators. As a general thing conductors are those substances which permit a current or charge to pass through them very readily, while insulators do not easily allow a current to pass. Some substances, however, will readily conduct certain kinds of electricity, while acting as insulators toward other kinds: thus dry wood readily conducts electrical charges while a dynamo current would be effectually barred by it. If the two terminals of a static machine are connected to a wooden table, the charges pass readily through the wood instead of between the discharging knobs. But if the two wires of an electric lighting circuit were approached within a half inch of each other and connected to the wood, no current would pass.

As the best known conductors offer some resistance to the passage of electricity, it may therefore be stated that there is **no perfect conductor.**

It is also true that the best known insulator will allow some electricity to leak through; therefore, there is **no perfect insulator.** The list of good conductors merges gradually into poor conductors and then into good insulators, and between the two extremes there is no sharp dividing line.

Among the best insulators are the following:

Mica	Shellac
Glass	Air
Porcelain	Paper
Rubber	Slate
Silk	Marble

One of the best insulators is mica, which possesses the valuable property of being fire proof as well as being of high specific resistance. Furthermore it does not diminish in resistance under mechanical pressure, and it does not readily absorb moisture.

Glass and porcelain are also excellent insulators. Glass, while possessing a high intrinsic resistance, has the undesirable quality of condensing moisture upon its surface. When exposed to the air, glass insulators accumulate a film of dust and moisture, which makes a coat of slime, and currents will leak over this surface from the wire to the pin which supports the insulator. In humid climates the loss through surface leakage is sometimes very great.

In this respect porcelain is superior to glass. Porcelain insulators do not readily condense moisture upon their surface. They are usually coated with a glaze consisting largely of silica. In the absence of this glaze the insulator might absorb moisture and become conducting. The protecting glaze prevents leakage through the insulator and also reduces surface leakage. Except for telephone, telegraph and other comparatively low voltage lines, porcelain insulators are preferred.

Gutta percha is a gum obtained from a tree similar to the India rubber tree, although not identical with it. It is a superior insulator for use on submarine cables. It is the only material that has been found which would successfully withstand the action of salt water indefinitely. Cables in service forty years show no deterioration whatever.

Vulcanized soft rubber is the best insulator for covering wires for electric lighting in buildings. To make the insulation adhere to the copper, the wire must first be coated with a layer of tin. This coating is to prevent the sulphur, which is used in vulcanizing the rubber, from oxidizing the wire. The rubber wall is generally ⅛″ or more in thickness and is protected by means of an outer braid of cotton saturated with a compound which resists moisture. This affords an insulation as a whole which is extremely high.

Paper forms an excellent insulator for the covering of wire provided it is impregnated with a moisture repellant which will stand a reasonably high temperature. Paper insulated cables have largely replaced those heretofore insulated with rubber, with a marked economy in cost. Paper covered cables, lead sheathed, are more homogeneous than those covered with rubber and are more easily manufactured, but the dielectric resistance of India rubber is greater than that of paper, so that paper covered cables must be larger and heavier to give the same amount of insulation. Furthermore, if the lead sheath is broken

a paper insulated cable is destroyed, as electrolytic action accompanying the introduction of moisture sets in rapidly. Paper is very largely used in electrical work both in the form of common paper and pressed board. It is frequently impregnated with paraffine or other hydro-carbons to render it impervious to moisture. Its dielectric powers decrease when it is subjected to an increase in mechanical pressure.

Although all oils are non-conductors, mineral oils are preferable as insulators because they do not gum. Vegetable oils have a tendency to become thick and gummy. They gradually carbonize under the application of heat. As they are thus slowly transformed into conductors their efficiency gradually becomes impaired. Switches designed to break circuits carrying high voltages are arranged to open the circuit under oil. A high grade mineral oil should be used for this purpose. The switch can be made much more compact than one designed to break a similar voltage in the air.

Among the manufactured insulators fibre is one of the best. This is a kind of paper, being manufactured from wood pulp. It is subjected to great hydraulic pressure and is made in rods, tubes, sheets and blocks, possessing considerable mechanical strength. It is made in various colors, chiefly red, white and black. The white hard fibre is one of the best in insulating properties. Most fibre tends to absorb moisture. Its insulating properties also diminish when it is subjected to mechanical pressure. Fibre also will carbonize under the application of heat or under the burning influence of an electric arc. When carbonized it becomes a conductor and its insulating properties immediately disappear. Fibre should never be used as an insulator for circuits of 500 volts and upwards.

Marble and slate have been extensively used as the insulating material for switchboards. Both may be sawed and drilled. Care should be taken, however, in the selection of such material, to see that it does not possess metallic veins which would destroy the insulating property. Slate is now used universally as switchboard material, being cheaper and more easily worked than marble. For voltages above seven hundred, however, even slate should not be relied upon, but switches for handling such circuits should be independently mounted and enclosed in oil, their operation being by remote control from a slate switch board on which the control circuits are operated at 110 volts.

One of the most widely used manufactured insulators is Bakelite. Dr. L. H. Baekeland discovered that carbolic acid, scientifically known as phenol, and formaldehyde can be made to unite chemically with each other so as to produce a solid, semi-transparent, amber-like substance without taste or odor and possessing entirely new chemical and physical characteristics. When these two materials combine a synthetic resin results, generally known as Bakelite. Certain solvents are available in which this resin may be dissolved, and thus varnishes and lacquers are made. If, however, this peculiar material is heated above a certain point, a secondary reaction of a chemical nature sets in. The material does not change its physical properties to any great degree, but the chemical change is remarkable and thereafter it becomes absolutely insoluble under any circumstances.

The Bakelite moulding process involves a temperature of 350 degrees Fahrenheit and a pressure of from 1,500 to 2,000 pounds per square inch of mould surface. Hardened steel dies are employed. The moulding material is prepared in the form of a dry, granular powder or in thin, hard sheets, which soften readily on being slightly heated. The first application of heat and pressure momentarily softens the material so that it fluxes freely and will accurately take the form of the mould. The continued application of heat and pressure brings about a chemical reaction which causes the moulded material to rapidly harden or set, after which it cannot be softened again by further heating. The time of this cure varies from five to eight minutes. After hardening, Bakelite has no melting point, but at temperatures in excess of 575 degrees it gradually carbonizes and disintegrates. Bakelite sheet, tube and rod consist of laminations of paper impregnated with Bakelite and compressed. It is vastly superior to hard rubber and fiber. It will not soften by heating nor absorb water or oil. It will not swell or warp and possesses an average dielectric strength of 930 volts per one-thousandth of an inch, with a tensile strength of 18,000 pounds per square inch. Micarta is the trade name of a Bakelite product in which the base is paper. It will stand a temperature of 150 degrees Centigrade continuously and is 50% stronger mechanically than the best hard fibre. A sample of Micarta one-eighth of an inch thick successfully withstood a pressure of 133,000 volts. Until Bakelite was invented, mica was the only

material with which commutators could be insulated. Now commutators can readily be constructed with Bakelite compound as the insulator, the body being about 50% wood pulp. The insulating properties are exceedingly high and the construction is so strong mechanically that small commutators will withstand speeds of 15,000 to 20,000 revolutions per minute without danger of going to pieces. Nearly every part of the electrical equipment of an automobile requiring insulation can employ Bakelite to advantage. Almost all of the leading lighting and ignition systems use Bakelite insulation for distributors and for all parts in the ignition system which require high insulation and ability to withstand the heat about an engine, under which rubber deteriorates and the poor insulating qualities of fibre invariably give way.

The best known conductors are the metals, carbon and water. Metals are all good conductors as far as static electricity is concerned. Carbon is a manufactured product obtained by mixing coke, which comes from gas retorts, with pitch for a binder. This is then baked in a furnace to produce rods and plates. A carbon rod of this kind possesses a resistance between two and three thousand times greater than a copper rod of the same dimensions.

Water is a conductor if it contains impurities, but it is a conductor only when impure. Chemically pure water has a conductivity of less than one-millionth of that of the metals. The slightest trace of impurity, however, greatly lowers its resistance. Thus a few drops of acid in a gallon of water will make the water a fair conductor. Dilute acids or acidulated water will conduct readily, but pure water and pure acids are poor conductors.

Ice is a non-conductor. It should be here noted that all transparent solids are non-conductors. For example, diamonds, quartz crystals, glass, mica and ice are all transparent solids and hence non-conductors.

The human body is a fair conductor. It is largely composed of liquid and although it often offers a high resistance to the passage of a current, this resistance is chiefly located at the contact point between the conductor and the hand or other portion of the body touched. If the skin be dry the resistance is high, but if the surface is moist the resistance is low.

Cotton, wood and paper depend for their insulating properties upon being thoroughly dry. They readily absorb moisture,

which rapidly lowers their insulating qualities. They must, therefore, be impregnated with some moisture repellant if they are to be of value as insulators.

Very small wires may be economically insulated with an enameled coating. When properly prepared and applied the enamel will not crack. It is non-inflammable and softens at about 300 degrees Fahrenheit. The enamel is a solution of cellulose acetate, which, when it solidifies, becomes a solid, transparent jelly. The bare wire is passed through a solution of the hot enamel and then cooled. It is then passed a second time through the enamel and again cooled. This is continued until the wire acquires from six to ten coatings. It is essential to work the enamel at the proper temperature to prevent cracking. Enamel has a higher insulation value than rubber for equal thicknesses. Two wires insulated with ten of these coatings may be placed in close contact and will stand a pressure of one thousand volts between them without breaking down. Enamel insulation is not practical for large wires, on account of the expense and because the insu'ation is readily fractured.

Bituminous substances such as tar, bitumen, and pitch are widely used as insulating material in cables. A mixture is used for underground cables which contains mineral pitch, silicon and tar. This is applied to a cable together with rough hemp in the proportion of one part hemp to two of the mixture. The bitumen used in electrical work, especially on cables, is largely vulcanized. For junction boxes bitumen is mixed with chalk or clay to obtain an economical filler. Its insulating power is not high and it can be used for low tension work only. The above substances are used principally in connection with the Edison system of underground conduits.

The metals in the order of their conductivity are as follows:

Silver..........	100%	Iron............	16%
Copper.........	98%	Lead...........	15%
Gold...........	78%	Tin.............	9%
Aluminum......	61%	Nickel..........	7%
Zinc...........	30%	Mercury........	1%
Platinum.......	17%		

The best known conductor is silver, and because of its excellent conducting qualities is used as a basis for comparison with other metals. For this purpose it is regarded as having a conductivity of 100%, although this does not mean that it is a perfect con-

ductor. Next in order comes copper, which, compared with silver, has a conductivity of 98%. This is the best commercial conductor. It is a singular fact that alloys of different metals have a conductivity which is often less than the conductivity of the poorest metal in the mixture. Thus, if an alloy is made of 50% copper and 50% silver, a conductivity is obtained which is not an average of the two, or 99%, but approximately only 68%. Copper is the most widely used conductor in the electrical industry. The cost of silver is prohibitive.

Since aluminum has been produced by electrical means the cost has been reduced to such an extent as to make it a formidable competitor of copper for transmission lines, where a bare conductor can be used. Because of its lower conductivity its cross-section has to be correspondingly increased in order to make the resistance comparative with equal lengths of copper.

In order that equal lengths of the two wires may have equal resistance, the cross-section of aluminum wire must have 159 circular mils if the cross-section of the copper wire is 100 circular mils. Although for equal cross-sections aluminum has a lower tensile strength than copper, for equal resistances the tensile strength of the larger aluminum wire is superior to the copper wire. The specific gravity of aluminum is so much less than copper, that for equal resistances and equal lengths an aluminum wire weighs only 48% of the weight of a copper wire. As the weight is thus somewhat less than one-half, it is evident that it would be economy to buy aluminum in place of copper, even though the price per pound were twice as much. Therefore, for equal conductivities, aluminum wire is cheaper at 38 cents per pound than copper at 19 cents. A further advantage lies in the fact that as aluminum wire is lighter and superior in tensile strength, the span between poles can be made longer and the cost of maintenance reduced. But the advantages which aluminum possesses are more than offset by some disadvantages if we attempt to use an insulated aluminum wire for pole lines or interior construction. This is on account of the greater amount of insulation required to cover the larger aluminum wire, which more than offsets the cheapness in cost of the bare wire and for interior work the superior tensile strength and lightness in weight are no advantage.

The only other conductor that is used extensively is iron. For equal conductivities, iron is the cheapest of all conductors.

While it has only about one-sixth of the conductivity of copper, its cost is less than one-sixth, so that if a conductor made of iron containing six square inches of cross-section be used, it would have the same resistance for a given length, and cost less than a copper conductor of one square inch of cross-section. The cost of manufacture of the insulating supports involved.for iron, however, would in general be prohibitive. Therefore, iron is rarely used as a conductor except in electric railway work where it is employed as a third rail on surface systems, or as a T-shaped rail in conduit or underground systems, when it is known as a conductor bar, and lastly, where both of the two rails of any electric railway system are employed as a common-return for conveying the current from the cars back to the power house.

Wires are generally made of circular cross-section. Because of the inconvenience involved in expressing these cross-sections in decimals of a square inch, it has been found convenient to adopt another method of measurement. The unit of measurement for the diameter of a wire is the **mil.** One mil is equal to one-thousandth of an inch. The unit of area for a wire is the **circular mil.** A circular mil is the area of a circle one mil in diameter. It is also the area of the largest circle that can be inscribed in a square mil. It is equal to 0.7854 of a square mil. To find the cross-sectional area of a piece of wire in circular mils, it is only necessary to square the diameter in mils; d^2 = c.m.

d = diameter in mils.

$c.m.$ = cross-section in circular mils.

For example: a wire has a diameter of $\frac{1}{4}$ inch and as it takes one thousand mils to make an inch, $\frac{1}{4}$ inch is equal to $\frac{1000}{4}$, = 250 mils. This is the diameter of the wire in mils. 250^2 = 62,500 c.m., cross-sectional area. If the cross-sectional area of a wire is known, its diameter may be found by extracting its square root. Thus, if a wire has a cross-section of 211,600 c.m. the diameter is the square root of this quantity, or 460 mils, which is $\frac{460}{1000}$, or 0.460 of an inch. This would represent a wire almost one-half of an inch in diameter. (500 mils = $\frac{1}{2}''$.)

In this country aluminum and copper wires are drawn to what is known as the Brown and Sharpe, or American gauge. The largest wire in this gauge is No. 0000. The wires decrease in size from this number up to No. 40. There is no fixed relation between the gauge number and the circular mils that holds throughout the table, although of course every particular size

wire is designated by a certain gauge number and also possesses a definite cross-section.

Some points regarding the wire table may be noted as of importance. Thus, proceeding from the larger wires to the smaller, and starting with any particular wire, it will be found that the third size smaller wire has one-half the cross-section. Thus, No. 10 has about one-half the circular mils of No. 7; No. 14 has one-half the circular mils of No. 11. It may also be observed that a wire which is ten gauge numbers smaller than another wire has one-tenth of its cross-section. Thus, a No. 20 has one-tenth the cross-section of a No. 10. A No. 15 has one-tenth the cross-section of a No. 5. A No. 7 has one-tenth the cross-section of a No. 0000.

The resistance of a wire varies directly with its length and inversely with its cross-section. Therefore, if the resistance of a certain wire one foot long is known, a wire 800 feet long of the same cross-section will have 800 times as much resistance. The larger the cross-section or area of the path for the current, the less will be the resistance of the conductor. Thus, if the resistance of a wire is two ohms for 800 feet of length, when it has a cross-section of 3,000 c.m., if its cross-section is doubled and thereby made 6,000 c.m. its resistance would be halved and would therefore be one ohm. The resistance of any conductor may be expressed by the following formula:

$$\frac{sp.r.\ l}{c.m.} = R.$$

$sp.r.$ = specific resistance of conductor, that is the resistance of a conductor one foot long and one circular mil in cross-section.

l = length of conductor in feet.

$c.m.$ = cross-section in circular mils.

R = total resistance in ohms per length of conductor.

The resistance of a copper wire one foot long, one mil in diameter and one c.m. in cross-section, at a temperature of about 75 degrees Fahrenheit, is 10.8 ohms. With this as a basis the resistance of a copper wire of any length and cross-section may be found. Thus, a No. 14 wire which has a c.m. of 4106, if 1600 feet long, will have a resistance of

$$\frac{10.8 \times 1600}{4106} = 4 \text{ ohms (approx.)}$$

SECTION I CHAPTER III

STATIC ELECTRICITY

CONDUCTORS AND INSULATORS

1. Define a conductor.
2. Define an insulator.
3. Give a list of some of the best insulators and the places where they would be used.
4. What are the relative advantages of glass and porcelain as insulators?
5. What are the relative advantages of gutta-percha, rubber and paper as insulators?
6. Where should fiber be used for insulating purposes, and where should it not be used?
7. For what purpose is slate chiefly used as an insulating material and where is it not suitable?
8. Explain the nature of bakelite, the method of preparation and some of its applications.
9. How do water, carbon and the metals rank as conductors?
10. To what class of materials do transparent solids belong?
11. Arrange in the order of their conductivities: gold, silver, iron, aluminum and copper.
12. What units are employed to designate the diameter and cross-sectional area of wires?
13. Define the "mil"; also the "circular mil."
14. If a wire has a diameter of 25 mils, what is its cross-sectional area in circular mils?
15. If a wire has a diameter of 3/16 inch, what is its cross-sectional area in circular mils?
16. If a wire has a cross-sectional area of 10,000 circular mils, what is its diameter in inches?
17. What are the relative conductivities of copper and aluminum wire of equal cross section?
18. What is the resistance of 1,500 feet of copper wire having a cross-section of 4,000 circular mils?
19. What is meant by a "mil-foot" of copper? What is its resistance?
20. What is the largest and the smallest wire in the Brown and Sharpe table?
21. What are the relative resistances of a No. 7 and a No. 10 wire?
22. How many wires of No. 30 gauge will it take to equal one No. 10 in cross-section?

STATIC ELECTRICITY

CONDENSERS

It has already been shown that oppositely electrified bodies attract one another. It has been found that if two oppositely electrified bodies are placed very close to each other their capacities will be greatly increased. In order to understand this action it will be necessary to explain the meaning of capacity, potential and quantity. Potential is derived from the Latin word "potens" which means power. The potential of a body is a measure of its power to do work.

A unit quantity of electricity has been defined as the amount of electricity which when placed at a distance of one centimeter in air from a similar and equal amount will repel it with a force of one dyne. **One unit quantity** of electricity imparted to a body which possesses **one unit of capacity** will electrify it to **one unit potential.** The relation existing between these three units is expressed in the following equation:

$$K=\frac{Q}{V}$$

K = capacity
Q = quantity
V = potential.

From the foregoing it will be seen that a small quantity of electricity will electrify a body of small capacity to a high potential. That is, 20 units of quantity imparted to a body having a capacity of four units, will electrify it to a potential of five units. Although a small quantity of water placed in a bottle or very slender vase would fill it to a high level, because its capacity is small, a considerable quantity may be imparted to a body possessing a large capacity, without electrifying it to a very high potential.

Suppose two metal discs, A and B, Fig. 14, are mounted on insulating supports and are approached to each other. Suppose the disc B is connected by a wire to a static machine or other source of high potential, so that it becomes charged positively. If disc A is connected by a wire to the ground, plate B will act

inductively across the dielectric, inducing a negative charge upon that part of the surface of plate *A*, nearest *B*. An equal positive charge will be repelled through the wire *G* to the earth. The pith ball electroscope connected with *A*, will show a feeble electrification while the one connected with *B* will be more h ghly electrified because of its connection with the static machine. The charge on the inner surface of *A* now reacts upon the inducing charge on *B*, attracting this positive charge to its inner surface and binding it there. This alteration in the distribution of the charge allows more positive charge to flow from the static

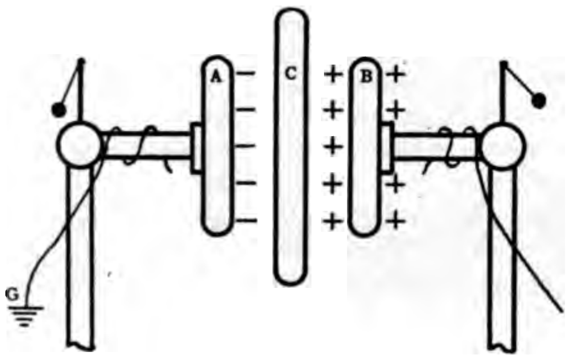


FIG. 14.—Illustrating the principle of a condenser.

machine. This increased positive charge upon *B* now reacts upon the plate *A* and induces from the earth a greater negative charge, which is attracted to its inner surface and condensed there. The increased negative charge again reacts upon *B*, attracting and condensing still more positive charge upon its inner surface. These two charges continue to increase in amount and condense upon the inner surfaces of the plates up to a potential equal to that of the source, or until the strain in the dielectric becomes so great that it can no longer support it mechanically. The dielectric then breaks down, a flash or spark passes across it, which is an indication of the tearing of a path through the dielectric as the two accumulated charges neutralize each other. If, before this discharge takes place, the wires connecting to the ground and static machine are removed and the plates approached more closely to each other, both pith ball electroscopes will descend, indicating apparently that there is less quantity present. This is not the case, however, but it

simply means that the capacity of the plates A and B have been increased, and for a given quantity an increase in capacity means a fall in potential, as will be seen from the foregoing formula. It is thus evident that the capacities increase as the conductors approach each other. If now the plates A and B are separated, their capacities fall, their potentials rise correspondingly and the pith balls again fly out, apparently indicating an increased amount of electrification. This, however, is due only to an increase in potential, caused by a diminution in capacity, for the charges do not now attract each other as powerfully and the condensing action is less when the plates are farther apart. If the plates A and B are separated by a slab of glass or mica instead of air, the inductive action will be greater. Such an arrangement is called a **Condenser.** Condensers are generally constructed with a dielectric made of paper, mica or glass, separating the metal coatings which are usually made of tin foil.

The capacity of a condenser depends upon three things:

First, upon the size and shape of the metal coatings.

Second, upon the thinness of the intervening dielectric.

Third, upon the dielectric capacity of the insulator separating the coatings.

It will be noticed that it makes no difference what metals are used. They may be of tin, sheet iron, tin foil, or any other material which is a good conductor. Their size and shape only are of consequence. As charges readily effect their escape from pointed conductors, the edges of the coatings of a condenser should be free from ragged points and should preferably be rounded on the corners. The capacity of a condenser will be increased directly with the size of the coatings. Thus, for a given thickness and quality of dielectric, doubling the size of the coatings would double the capacity of the condenser.

The closer the coatings are together, the greater will be the resulting attraction. As it is desirable to make the capacity great, the dielectric should be as thin as possible, and yet be able to mechanically support the strain. If the dielectric is too thin or is not sufficiently tough, the pressure of the two charges upon its surface will tear a path through it, and the two charges will neutralize each other over this path.

The dielectric capacity of the material which separates the coatings is different for different materials. The dielectric

capacity of air is taken as one. Mica has values ranging from 5 to 8, glass is about 3, shellac 2.74, turpentine and petroleum have a capacity of about 2. These represent the relative amounts of inductive action that will occur through equal thicknesses of these materials.

A plate condenser consists of a pane of glass on the two sides of which are glued pieces of tin foil. Fig. 15. These coatings should extend to within about 1½ inches of the edge all around.

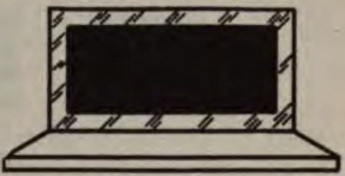


FIG. 15.—Simple plate condenser.

A more compact form of condenser may be made in the shape of a glass jar which is coated with tin foil on the inside and outside, on the bottom and about half way up the sides. A wire connecting with the inner coating passes through a cork by which the jar is sealed, and terminates in a knob. This is, in effect, nothing but a plate condenser rolled up, except that in the plate condenser both coatings are insulated from the ground, while in this latter form the outer coating may rest upon the table and is consequently grounded. This does not interfere with its capacity, however, as the charge upon the inside of the jar will effectually bind and hold the charge on the outside.

FIG. 16.

This arrangement, Fig. 16, is commonly known as a Leyden Jar, and derives its name from the town of Leyden, where its action was first discovered. These jars may be employed singly or in batteries. Two methods of connecting them up are possible. One, in which the inner coating of one is connected to the outer coating of the next, and the inner coating of the second to the outer coating of still another, and so on. The jars in this case must be mounted on an insulating glass plate. If the inside coating of one jar and the outside coating of the jar upon the other end be connected to brass knobs, as illustrated in Fig. 17, and the jars be charged by a static machine, the inductive and condensing action will take place through all the jars. When they are charged to such an extent that the air space between the two knobs can no longer support the strain, the dielectric is broken down and a spark

passes from one knob to the other. This arrangement is known as a **series connection.** Originally it was called a "cascade connection." It is found that the electrical pressures in the

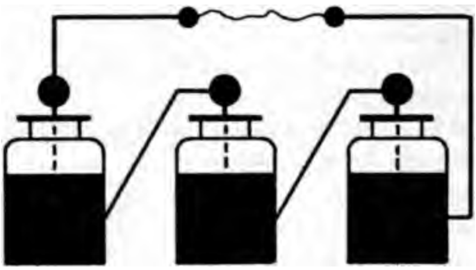


FIG. 17.—Leyden jars in series.

jars when so connected are all added, so that if the jars were each separately charged from a static machine and then connected in series the length of the spark between the two knobs would be three times as great as could be obtained from one although the thickness of the spark will be the same as with one jar.

The other method of connecting Leyden jars in a battery is shown in Fig. 18. This is known as a **multiple connection** or a connection for quantity. Here, all of the outer coatings are connected together and terminate in a knob while all of the

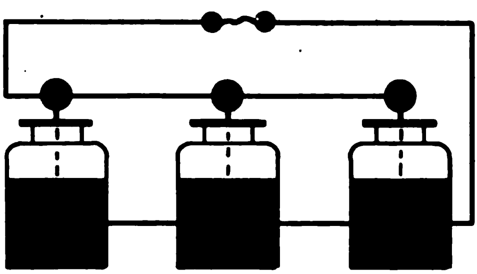


FIG. 18.—Leyden jars in multiple

inner coatings are similarly connected and terminate in another knob. When charged from a static machine, the length of the spark that is now obtainable is only that which one jar could have supplied, but the thickness or fatness of the spark is three times as great, indicating that the volume of the charge has been increased.

If a Leyden jar is charged and subsequently discharged by bringing the inner and outer coatings into metallic contact it will be found that if it is allowed to rest a while, it is capable of again furnishing a discharge, and another spark may be obtained. This second spark is due to the **residual charge** which seems to have soaked into the glass or been absorbed by it. It is found only in condensers possessing a solid dielectric. No such effect is possible in a condenser with an air dielectric.

In order to find where the charge actually resides, Franklin constructed a Leyden jar with separable metallic coatings, Fig. 19. He then charged the jar and by insulated handles removed the inner and outer coatings. Examining them he found that they contained practically none of the original charge. Neither was the glass found to be electrified to any great degree. But again putting the coatings in place, it was found that the jar was capable of giving a powerful discharge. It was therefore evident that the charge did not reside on the coatings of a condenser but that it resided on and in the surface of the dielectric. As a dielectric is a poor conductor it would be difficult to distribute the charges over its surface. The coatings, being good conductors, readily distribute the charge over the surface of the dielectric, where it remains until a conducting path is provided between the two coatings. When a condenser is discharged, only the portions of the charges on the immediate surface are neutralized. After a time the remainder of the charge which has been drawn by the powerful attractions into the pores of the glass, gradually comes to the surface through the poor conducting glass. The removal of the tension in the dielectric permits this action. This accounts for the residual charge found in a condenser.

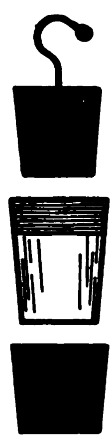


FIG. 19.

SECTION I CHAPTER IV

STATIC ELECTRICITY

CONDENSERS

1. If a body possessing 4 units of capacity is electrified to 5 units of potential, what quantity does it contain?

2. If a body containing 30 units of quantity is electrified to 5 units of potential, what is its capacity?

3. If a body possessing 3 units of capacity contains 30 units of quantity, what is its potential?

4. A body possesses a fixed quantity of charge. If its capacity is increased, what will be the effect upon its potential?

5. Upon what three things does the capacity of a condenser depend?

6. What is the construction of a Leyden jar?

7. Where does the charge in a condenser reside? Give a proof.

8. In what two ways may Leyden jars be connected? What is the effect upon the quantity and potential obtained in the two cases?

9. Each unit of a battery of Leyden jars is charged with 10 units of quantity to a potential of 10,000 volts. What will be the potential and quantity delivered by three such jars: (*a*) When they are connected in series. (*b*) When they are connected in multiple.

10. What is the residual charge in a condenser? How may it be obtained? When is there no residual discharge?

11. Mention a number of the best dielectrics.

12. Explain the construction of any standard form of condenser. What materials are used and what are their advantages?

SECTION II CHAPTER I

UNITS AND DEFINITIONS

FUNDAMENTAL AND DERIVED UNITS

All physical quantities, such as force, velocity, mass, etc., can be expressed in terms of three fundamental units. These are the

Centimeter, the unit of length;

Gram, the unit of mass;

Second, the unit of time.

These constitute the basis of what is called the **C-G-S,** or the "Centimeter-Gram-Second system" of units.

The centimeter is equal to 0.3937 of an inch, It is the $1/100$ part of a meter. One meter is equal to 39.37 inches; 2.54 centimeters equals 1 inch. The centimeter is represented by the symbol **cm.**

The gram is a unit of mass. It is a measure of the amount of matter which a body contains. There is a distinction to be made between mass and weight. By weight is meant the force with which the earth attracts a given mass. Therefore, the attraction at the earth's surface for a given mass may be expressed in pounds. On this basis one gram is equal to $1/453{\cdot}6$ pounds. The symbol for the gram is **g.**

The second is the $1/60$th part of a minute. The symbol for the second is **s.**

From the fundamental units there are derived two systems of electrical units. First, the **Electrostatic System** which is based on the force exerted between two quantities of electricity. Second, the **Electromagnetic System** which is based upon the force exerted between a current and a magnetic pole.

The units in the Electrostatic System are as follows:

Quantity	—(q) Divided by 3×10^9 = coulombs.
Current	
Potential Difference	—(e) Multiplied by 300 = volts.
Resistance	
Capacity	—(k) Divided by 900,000 = microfarads.
Specific Inductive Capacity.	

No names are given to these units. They are always defined in terms of other units of the same system, or may be reduced to practical units as above indicated. Thus, an electrostatic unit of quantity of electricity is such a quantity that when placed at a distance of one centimeter in air from a similar and equal quantity will repel it with a force of one dyne. To reduce this unit to coulombs, which is a practical unit, it must be multiplied by 3×10^9.

The **Electromagnetic System** is subdivided into two parts:

First, the **Magnetic Units.**

Gauss	(B)	Unit of Magnetic Induction.
Maxwell	(Φ)	Unit of Total Magnetic Flux.
Gilbert	(F)	Unit of Magneto-Motive-Force.
Oersted	(R)	Unit of Magnetic Reluctance.
Strength of pole.		No name.
Magnetizing Force.		No name.
Permeability.		No name.
Susceptibility.		No name.
Reluctivity.		No name.

Second, the **Electromagnetic Units.**

Strength of Current.
Difference of Potential.
Resistance
Quantity.
Capacity.
Induction.

While names are given to some of the magnetic units as indicated, no names are assigned to the electromagnetic units. They are defined in terms of each other as are the electrostatic units.

Some of the electromagnetic units are inconveniently large, while others are inconveniently small for practical purposes There are, therefore, a number of practical electromagnetic units which are derived from the foregoing absolute electromagnetic system and are of convenient size for practical work. Following the name of the unit is given the symbol which represents it, its equivalent in absolute electromagnetic units, and its definition.

Volt (E) (10^8) — The unit of electrical pressure. Electromotive force. (e.m.f.) Potential difference.

Ampere (I) (10^{-1}) — The unit of intensity of current; rate of flow; volume. One ampere will deposit silver in an electrolytic cell at the rate of 0.001118 gram per second.

Ohm (R) (10^9) — The unit of resistance; a column of mercury 106.3 cm. long and having a mass of 14.4521 grams (approximately 1 square millimeter cross-section) at 0 degrees Centigrade has a resistance of one ohm.

Coulomb (Q) (10^{-1}) — The unit of quantity; one ampere flowing for one second will transfer one coulomb through a circuit past a fixed point.

Watt (P) (10^7) — The unit of power; rate of doing work. The product of the volts applied and the current flowing in a circuit. One ampere $\times$ one volt = one watt.

Joule (W) (10^7) — The unit of work; force acting through distance.
One ampere $\times$ one volt $\times$ one second = 1 Joule. One watt $\times$ one second = 1 Joule. One coulomb $\times$ one volt = 1 Joule.

Farad (C) (10^{-9}) — The unit of capacity. A condenser has a capacity of one Farad when one coulomb delivered to it will raise its potential one volt.

Henry (L) (10^9) — The unit of electromagnetic induction. A circuit possesses a self-induction of onc Henry when a rate of current variation of 1 ampere per second causes thegeneration therein of one volt.

In order to express very large quantities in a condensed form a system of index notation is adopted, which is employed in connection with the above units. This obviates the use of a long row of ciphers. In this system the significant figures only of a quantity are put down, the ciphers at the end being indi-

cated by an index written above. Thus 1,000 may be written as 10^3. Fractional quantities may be expressed by negative indices written as exponents. Thus $1/100 = 10^{-2}$. The resistance of air is about 10^{26} times that of copper. If this is expressed with ciphers it would be necessary to say that the resistance of air is equal to 100,000,000,000,000,000,000,000,000 times that of copper.

To express fractional parts of units or multiples of quantities involving the above units, certain prefixes are employed.

Thus, the prefix **Micro** means $1/1,000,000$ part of the quantity to which it refers. A microfarad is therefore one one-millionth part of a farad.

The prefix **Milli** means the $1/1,000$ part of the quantity to which it refers. A milliampere is therefore one one-thousandth of an ampere.

The prefix **Centi** means the $1/100$ part of the quantity to which it refers. Thus a centimeter is one one-hundredth of a meter.

The prefix **Mega** means 1,000,000 times the quantity to which it refers. Thus a megohm is equal to one million ohms.

The prefix **Kilo** means 1,000 times the quantity to which it refers. Thus a kilowatt is equal to one thousand watts.

The prefix **Hekto** means 100 times the quantity to which it refers. Thus a Hektowatt is equal to one hundred watts.

SECTION II CHAPTER I

UNITS AND DEFINITIONS

FUNDAMENTAL AND DERIVED UNITS

1. Explain the basis of the "C. G. S." system of units. Define each unit in the system.

2. How many centimeters are in an inch? How many inches are in a centimeter? How many inches are in a meter? How many square centimeters are in a square inch?

3. Explain the basis of the electrostatic system of units. Mention the principal units.

4. Explain the basis of the electromagnetic system of units. Mention the principal units.

5. What are the absolute electromagnetic units?

6. Explain the necessity for the practical electromagnetic units.

7. Define the volt.

8. Define the ampere.

9. Define the ohm.

10. Define the coulomb.

11. Define the watt.

12. Define the joule.

13. Define the farad.

14. Define the henry.

15. Translate into words the following expressions: 10^6; 10^9; 10^{-2}; 10^{-6}.

16. Define the following abbreviations: "milli"; "centi"; "deci."

17. A millimeter is equal to how many meters? A centimeter is equal to how many meters? A decimeter is equal to how many meters?

18. Define "hekto," "kilo," and "mega." A "megawatt" is equal to how many watts? A "kiloampere" is equal to how many amperes? A "hektovolt" is equal to how many volts?

UNITS AND DEFINITIONS

OHM'S LAW

George Simon Ohm was born in 1789. His father was a humble locksmith, but an able mathematician. He taught his son mathematics and the locksmith's trade. Young Ohm grew up to love electrical research work. "The Galvanic Battery Treated Mathematically" has become a classic of science. He published this in Berlin in 1827. The discovery of the law governing the flow of current in an electrical circuit was made in 1781 by Cavendish. But until Ohm obtained results by experiment, the law was not publicly recognized. In 1841 the Royal Society of England honored him with a gold medal for "the most conspicuous discovery in the domain of exact investigation."

The law which bears his name, known as "Ohm's Law," shows the relation existing between the current, the e.m.f. and the resistance in an electrical circuit. The law is exact and absolutely true. It has sometimes been thought that Ohm's law was not accurate when dealing with alternating currents. When, however, everything is considered, it is perfectly true under every circumstance. The fundamental statement of Ohm's Law is as follows:

The intensity of the current in amperes in any electrical circuit, is numerically equal to the e.m.f. in volts impressed upon that circuit, divided by the entire resistance of the circuit in ohms.

The equation as usually expressed is,

$$I = \frac{E}{R}$$

I = intensity of current in amperes.
E = e.m.f. in volts.
R = resistance in ohms.

This equation may be transposed so that knowing any two of the quantities, the third may be ascertained.

Thus,

$$R = \frac{E}{I}.$$

$$E = IR.$$

If the e.m.f. in a given circuit is 20 volts and the resistance is 5 ohms, the current which will flow is—

$$\frac{20}{5} = 4 \text{ amperes,}$$

or, if the e.m.f. given was 20 volts and a current of 4 amperes flowed, the resistance of the circuit would be—

$$\frac{20}{4} = 5 \text{ ohms.}$$

Or, if the current given was 4 amperes and the resistance 5 ohms, the e.m.f. impressed on the circuit must be $4 \times 5 = 20$ volts.

As it is sometimes difficult to remember these equations, a simple expression for all three may be arranged as follows: Describe a circle and divide it horizontally in the center. In the upper half write *E;* in the lower half write *IR*. Fig. 20. Now, knowing any two of the three quantities, insert them adjacent to the corresponding letters. Place the finger over the unknown quantity. The relation expressed between the other two will give the value of the unknown to be obtained.

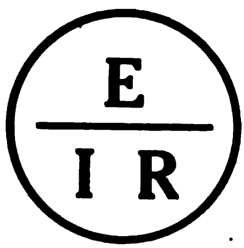


FIG. 20.

The next deduction from this law is the statement that the current in any electrical circuit will vary directly with the e.m.f. and inversely with the resistance. That is to say, in the preceding example if the e.m.f. is raised from 20 to 40 volts, then the current will be raised in precisely the same ratio; i.e., from 4 to 8 amperes, provided the resistance is not changed. Thus, increasing or diminishing the e.m.f. will increase or diminish the current in the same way. If, however, the resistance had been doubled from 5 to 10 ohms, while the pressure remained constant, the current would have been reduced from 4 to 2 amperes, which is in accordance with the above statement that the current in an electrical circuit varies inversely with the resistance.

If the current in an electrical circuit is to be maintained constant, the resistance must be varied directly with the e.m.f.; while if the e.m.f. is to be kept constant, the resistance must be varied inversely with the current. Thus, if the current is 4 amperes and the e.m.f. is increased from 20 to 40 volts, the resistance must

be increased from 5 to 10 ohms to prevent the current changing. Or, if the e.m.f. is to be maintained constant at 20 volts, then in order to halve the current or change it from 4 amperes to 2, it will be necessary to double the resistance and raise it from 5 to 10 ohms.

The e.m.f. in a circuit varies directly with either the current or the resistance. It is therefore proportional to their product. Thus, suppose the e.m.f. is 20 volts, the current 4 amperes and the resistance 5 ohms, as before. If the current is raised to 8 amperes, the e.m.f. must be raised in the same proportion to 40 volts to maintain this current if the resistance remains fixed. Or, if the resistance is raised from 5 to 10 ohms while the current remains at 4 amperes, the e.m.f. must be raised in the same proportion from 20 to 40 volts.

Another series of equations may be established which are related to Ohm's Law because of the fact that the power in watts in any electrical circuit is equal to the current in amperes, multiplied by the e.m.f. in volts. Thus,

$$P = IE.$$

The current may be found by dividing the power by the e.m.f. Thus,

$$I = \frac{P}{E}.$$

The e.m.f. may be found by dividing the power by the current. Thus,

$$E = \frac{P}{I}.$$

These relations may be easily remembered by constructing a circle similar to the one for Ohm's Law, Fig. 21. Divide the circle horizontally in the middle. Place the letter P in the upper half and IE in the lower half. Knowing any two of the three quantities, place them beside the corresponding letters, then putting the finger over the unknown quantity, the relation expressed between the other two enables the value of the unknown to be obtained. Thus, if the power in a circuit is 80 watts and the e.m.f. is 20 volts, by substitution, 80 divided by 20 equals 4 amperes.

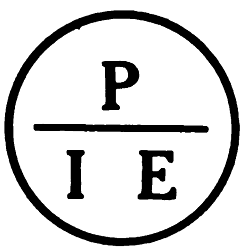


FIG. 21.

The current in any circuit is proportional to the power if the e.m.f. remains fixed. The e.m.f. in any circuit is proportional to the power if the current remains fixed. It may be stated that the power in any circuit varies directly with the current or with the e.m.f.; it is therefore proportional to their product. In the foregoing example, if the e.m.f. is raised from 20 to 40 volts while the current is maintained at 4 amperes, the power will be raised from 80 to 160 watts. If the current is raised from 4 to 8 amperes while the e.m.f. is maintained at 20 volts, the watts will also be raised from 80 to 160. But if the current is raised from 4 to 8 amperes, and the volts are raised from 20 to 40, the watts are raised from 80 to 320, which is the product of the current and the voltage.

As the current and voltage are both involved in both sets of the foregoing equations, a third set of equations may be developed from which two unknown quantities may be obtained by knowing the other two. In the first set of equations $IR = E$, and in the second set $IE = P$. By substituting the value of E from the first equation in place of E in the second, as $IIR = P$, or $I^2R = P$, from which the value of R may be found.

$$R = \frac{P}{I^2}. \qquad I^2 = \frac{P}{R}. \qquad I = \sqrt{\frac{P}{R}}.$$

These three quantities may also be arranged in a circle. P is placed in the upper half and I^2R in the lower half. (Fig. 22.) Inserting in this circle the values of the preceding example gives

$$\frac{80}{5} = 16, \text{ which is } I^2.$$

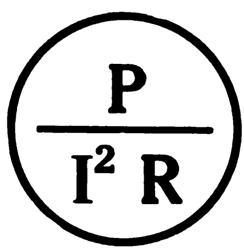


Fig. 22.

Notice that this is the square of the current and not the simple current. The square root of 16 is 4. Now, having ascertained I to be 4 and R to be 5, E is found from the first formula to be 20. Thus, when the watts and resistance only are given, the current and the e.m.f. may be calculated.

Another set of equations may be obtained as follows: In the first case,

$$I = \frac{E}{R}.$$

In the second case,

$$EI = P.$$

Substituting the value of I from the first equation in the second gives—

$$\frac{EE}{R} = \frac{E^2}{R} = P,$$

and

$$\frac{E^2}{P} = R.$$

Then

$$E^2 = RP \text{ and } E = \sqrt{RP}.$$

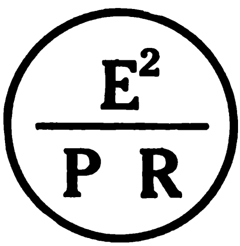


FIG. 23.

These equations may be arranged in a circle as before, in which case E^2 should be placed in the upper half and PR in the lower half. (Fig. 23.) The unknown quantity can be calculated from this circle if two of the quantities are known. This latter series of equations are not often used, as the preceding ones will answer every purpose.

SECTION II CHAPTER II

UNITS AND DEFINITIONS

OHM'S LAW

1. State Ohm's Law in its simplest form (in words).

2. State Ohm's Law as an equation, using the customary letters for each quantity. (Tabulate the meaning of each letter used.)

3. Give three equations for Ohm's Law for determining the value of current, e.m.f. and resistance.

4. Give three equations for the power in an electrical circuit when it is desired to know the watts, amperes or voltage.

5. Give three equations for the power in an electrical circuit when the quantities involved are watts, current and resistance.

6. Give three equations for the power in an electrical circuit when the quantities involved are voltage, watts and resistance.

7. A motor absorbs 650 watts. It is designed for 100 volts. How many amperes does it require?

8. A lamp has a resistance of 100 ohms and takes 1 ampere. How many watts does it absorb?

9. A coil is designed to take 5 amperes from 110-volt circuit. What is its resistance and how many watts does it absorb?

10. A motor has an equivalent resistance of 6 ohms and absorbs 2.4 k.w. How many amperes does it take? For what voltage is it designed?

11. A battery having an internal resistance of 3 ohms is connected in series with an external resistance of 6 ohms. The e.m.f. is 1.8 volts. What current will flow?

12. A battery having an internal resistance of 4 ohms is connected in series with an external resistance of 6 ohms. A current of 5 amperes circulates. What is the voltage of the battery?

13. A current of 8 amperes circulates through a total resistance of 3 ohms. What is the required voltage?

UNITS AND DEFINITIONS

LAWS GOVERNING SIMPLE ELECTRICAL CIRCUITS

A **series circuit** is one in which all of the electrical devices are looped in series upon the circuit, which consists of but one wire, Fig. 24. This is the common arrangement for arc and incan-

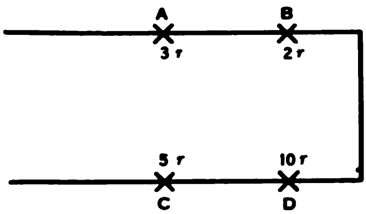


FIG. 24.—Series circuit.

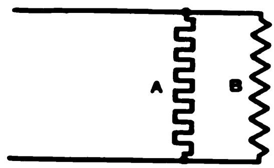


FIG. 25.—Branch circuit.

descent lamps used in street lighting. The current is the same in all parts of such a circuit.

A **branch circuit** is one in which the circuit divides, as shown in Fig. 25, the currents in *A* and *B* again uniting in the common wire. This is also called a **divided circuit.**

A **multiple** or **parallel** circuit, Fig. 26, is one in which all of the electrical devices are connected in parallel paths between the two main wires of the circuit. The voltage impressed upon these

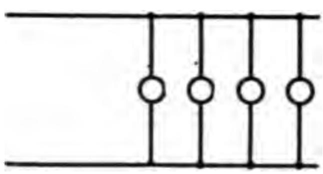


FIG. 26.—Multiple circuit.

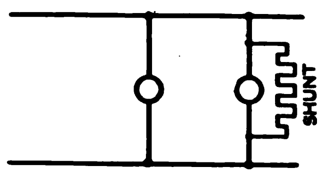


FIG. 27.—Shunt circuit.

various paths is the same in any case, but the currents in the different branches depend upon the resistance of each branch.

A **shunt circuit** is a by-path, usually of high resistance, Fig. 27. Although the shunt used with electrical measuring instruments is of very low resistance, the shunt strap is really the main path and the instrument itself forms the true shunt thereto. As incandescent lamps are of high resistance it may be said that the lamps shown in Fig. 26 are connected **in shunt.** Therefore,

branched, divided, parallel and **shunt** circuits are very similar, if not identical.

A **short circuit** is a path of practically no resistance between the terminals of an electrical source, Fig. 28. Even though lamps

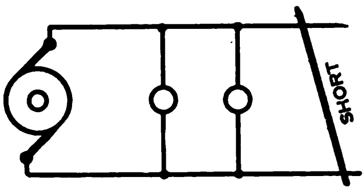


FIG. 28.—Short circuit.

be connected nearer to the dynamo than the short circuit, the current will take the path through this negligible resistance in preference to the lamps. The term **short** refers to the relative **resistance** of the paths and not to the actual lengths.

The resistance of a series circuit is equal to the sum of all the separate resistances therein. Thus, the combined resistance of 3, 2, 5 and 10 ohms in series shown in Fig. 24, is 20 ohms.

The current which circulates in a series circuit is equal to the algebraic sum of all the e.m.fs. therein, divided by the arithmetical sum of all the resistances. Thus, if two cells of battery are connected in series to furnish a combined e.m.f. of 4 volts, and two more cells which furnish 3 volts are connected in series with the first but with their e.m.fs. in the opposite direction, then the net e.m.f. of all four will be 4 minus 3 volts, or 1 volt, Fig. 29. If each of these four cells has an internal resistance of 0.5 ohm and they are connected in an external circuit whose resistance is 5 ohms, then the total resistance will be 4 times 0.5 ohm or 2 ohms internal, plus 5 ohms external, or 7 ohms total resistance. One volt effective e.m.f. divided by 7 ohms resistance will produce a current of one-seventh of an ampere.

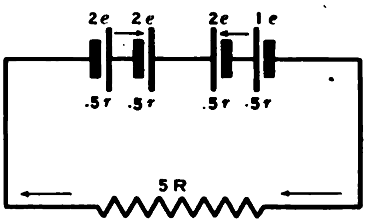


FIG. 29.—Calculation of current in series circuit with electro-motive-forces in opposition.

The combined resistance of any number of equal resistances in multiple may be found by dividing the resistance in one branch

by the number of branches. Thus, if 5 lamps of 10 ohms resistance each are connected in parallel, the combined resistance of the five will be

$$\frac{10}{5} = 2 \text{ ohms. See Fig. 30.}$$

The combined resistance of two unequal resistances in multiple is equal to their product divided by their sum. Thus, if

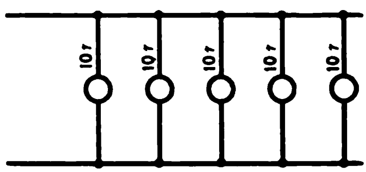


FIG. 30.—Calculations of equal resistances in multiple.

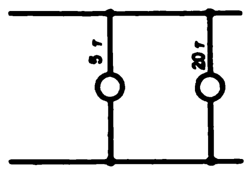


FIG. 31.—Calculation of two unequal resistances in multiple.

5 ohms and 20 ohms are placed in multiple, their combined resistance is:

$$\frac{5\times 20}{5+20} = \frac{100}{25} = 4 \text{ ohms. See Fig. 31.}$$

The combined resistance of any number of unequal resistances in multiple is equal to the reciprocal of the sum of the reciprocals of the separate resistances. This is because resistances in multiple do not form added resisting paths. They do, however, form

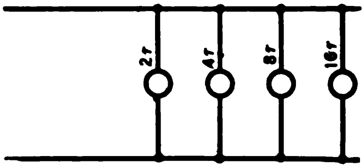


FIG. 32.—Calculation of any number of unequal resistances in multiple.

added conducting paths. It is therefore necessary to express their separate resistances as conductances after which they may be added. Conductance is the reciprocal of resistance. The reciprocal of a number is one divided by that number. Therefore, if a branch possesses 2 ohms resistance, ½ represents the conductivity of that branch.

Consider a circuit composed of 4 branches consisting of 2, 4, 8 and 16 ohms resistance, respectively, Fig. 32. The expression for the combined resistance will be

$$\frac{1}{\frac{1}{a}+\frac{1}{b}+\frac{1}{c}+\frac{1}{d}\cdots\cdots\cdots} = R.$$

The relative conducting paths are expressed as the reciprocals of these resistances; $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$, $\frac{1}{16}$. In order to place them on the same basis, so as to add them, they must be reduced to a common denominator. This will give $\frac{8}{16}+\frac{4}{16}+\frac{2}{16}+\frac{1}{16} = \frac{15}{16}$. As the reciprocal of resistances is conductance, the word **ohm** has been reversed and spelled backward to make **mho,** which is the unit of conductance. The combined conductance of the circuit is therefore $\frac{15}{16}$ mhos. As resistance was inverted to obtain conductance, so conductance may be inverted to give resistance. Thus, $\frac{15}{16}$ mhos $= \frac{16}{15} = 1\frac{1}{15}$ ohms, which is the combined resistance.

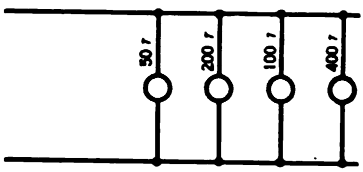


FIG. 33.—Calculation of various resistances in multiple.

Substituting,

$$\frac{1}{2}+\frac{1}{4}+\frac{1}{8}+\frac{1}{16}=\frac{8}{16}+\frac{4}{16}+\frac{2}{16}+\frac{1}{16}=\frac{15}{16}\text{ mhos,} = 1\frac{1}{15}\text{ ohms.}$$

In multiple circuits, each branch passes a portion of current which is inversely proportional to its resistance. Thus, if two branches possess 5 ohms and 3 ohms respectively, and a current of 8 amperes divides between them, the 5 ohm resistance will receive 3 amperes and the 3 ohm resistance will pass 5 amperes. In other words, if the resistances are in ratio of 5 : 3 the currents will divide in the ratio of $\frac{1}{5}$: $\frac{1}{3}$, or 3 : 5.

Consider a multiple circuit, Fig. 33, in which there are 4 branches of 50, 200, 100 and 400 ohms, respectively. Let a current of 45 amperes from a generator be divided among these four branches. How much current will each branch pass?

The resistances must first be reduced to conductances. Thus $\frac{1}{50}$, $\frac{1}{200}$, $\frac{1}{100}$, $\frac{1}{400}$. Reducing these to a common denominator gives $\frac{8}{400} + \frac{2}{400} + \frac{4}{400} + \frac{1}{400} = \frac{15}{400}$. The common denominator, 400, can be abolished without altering the value of the equation. The total conductivity of the four paths may be represented as 15, the sum of the numerators. Then, out of the 45 amperes, the first branch will receive 8 parts out of 15, or $\frac{8}{15}$ of 45 amperes, which equals 24 amperes in the 50 ohm resistance. The second branch will receive $\frac{2}{15}$ of 45 amperes, or 6 amperes in the 200 ohm resistance. The third branch will receive $\frac{4}{15}$ of 45 amperes or 12 amperes in the 100 ohms. The last branch will receive $\frac{1}{15}$ of 45 amperes in the 400 ohm resistance, or 3 amperes.

$$\frac{1}{50}+\frac{1}{200}+\frac{1}{100}+\frac{1}{400}=\frac{8}{\cancel{400}}+\frac{2}{\cancel{400}}+\frac{4}{\cancel{400}}+\frac{1}{\cancel{400}}=\frac{15}{\cancel{400}}$$

$\frac{8}{15}$ of 45 amperes = 24 amperes in 50 ohm branch.
$\frac{2}{15}$ of 45 amperes = 6 amperes in 200 ohm branch.
$\frac{4}{15}$ of 45 amperes = 12 amperes in 100 ohm branch.
$\frac{1}{15}$ of 45 amperes = 3 amperes in 400 ohm branch.

$24 + 6 + 12 + 3 = 45$ amperes which the generator furnishes. The current is thus all accounted for. The 200 ohm resistance receives 6 amperes; the 100 ohm resistance receives 12 amperes. Thus ½ the resistance absorbs twice the current, which is in accordance with the above law.

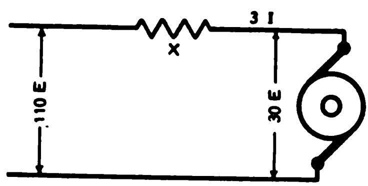


Fig. 34.—Calculation of resistance required in series with motor to adapt it for a higher voltage circuit than that for which it is wound.

Suppose it is desired to operate a motor requiring 3 amperes and 30 volts upon a 110 volt constant potential circuit, Fig. 34. How much resistance must be placed in series with the motor in order that it may obtain its proper current?

The apparent resistance of the motor will be expressed by the equation

$$R=\frac{E}{I}.$$

Where E and I are the voltage and current required by the motor.

$$\frac{30}{3} = 10 \text{ ohms.}$$

If the entire circuit is to carry but 3 amperes, the necessary resistance to limit the current will be:

$$\frac{E}{I} = R.$$

Where E is the voltage of the line and I the current required by the motor.

$$\frac{110}{3} = 36\tfrac{2}{3} \text{ ohms.}$$

As the motor's apparent resistance is 10 ohms and the total resistance required is $36\frac{2}{3}$ ohms, the necessary resistance to be placed in series with the motor will be the difference between 10 and $36\frac{2}{3}$, or $26\frac{2}{3}$ ohms.

It is sometimes considered desirable to place a resistance in shunt as well as in series with a motor, Fig. 35. This arrangement will steady the operation of the motor if its voltage is much below the line voltage. Suppose that the above motor is to be operated in series with a 20 ohm resistance coil, on a 110 volt circuit. How much resistance must be placed in shunt with the motor in order that it shall obtain its proper voltage and current? As the motor is to receive 30 volts and the line voltage is 110, it is necessary that the 20 ohms resistance in series shall absorb the difference between 30 and 110, or 80 volts. The question then, is, how much current must be passed through a

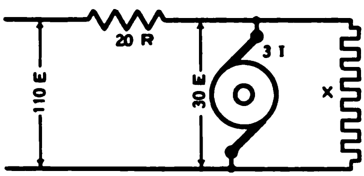


FIG. 35.—Calculation of resistance required in shunt with motor to adapt it for operation on a higher voltage circuit than that for which it is wound when placed in series with a given resistance.

20 ohm resistance in order that a drop of potential of 80 volts shall be produced therein? According to Ohm's law the current required will be:

$$\frac{E}{R} = I.$$

$$\frac{80}{20} = 4 \text{ amperes.}$$

Thus 4 amperes is brought up to the motor terminals. Of this the motor will take 3 amperes and the balance, one ampere, must be conducted around through the shunt. The difference of potential between the motor's terminals and also the terminals of the shunt coil is 30 volts. The question then is how many ohms resistance will be required, to limit the current to one ampere under a pressure of 30 volts. From Ohm's Law we have:

$$\frac{E}{I} = R$$

$$\frac{30}{1} = 30 \text{ ohms, the required resistance of the shunt.}$$

A **multiple-series** circuit is one in which the main circuit consists of branches connected in **multiple,** while the individual units which make up these branches are connected in **series.** This is illustrated in Fig. 36. Here are two sets of lamps connected in multiple. Each set consists of 5 lamps in series. It is

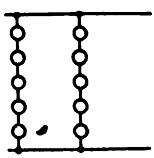


FIG. 36.—Multiple-series circuit of lamps.

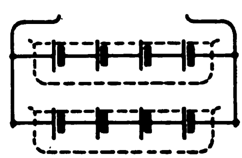


FIG. 37.—Multiple-series circuit of batteries.

therefore a **multiple of series.** A similar arrangement for batteries is shown in Fig. 37. Here are 4 cells in series. These constitute in effect one large cell. Below is shown another set of 4 cells in series. These two sets, which constitute practically two large cells are then connected in multiple. There are only 4 cells in series, not 8, because the first set is in multiple with the second set. It is therefore a multiple-series connection.

Incandescent lamps in street-cars are connected in multiple-series. Five 110 volt lamps are connected in series on a 550 volt line. If more lamps are required, an additional series of 5 lamps is run and connected in multiple with the first set. A street car will generally have multiples of 5 lamps; thus, 10, 15 or 20.

Arc lamps are connected in series as shown by × in Fig. 38. When such a circuit was the only one available, incandescent lamps were sometimes connected in multiple and placed in series on such a line as at *A*. If the current in the main line is 4 amperes, it will be necessary to place at least 4 incandescent lamps carrying one ampere each in multiple and then connect them in series with the main line. The 4 amperes passing through an arc lamp will then divide through the four branches of the incandescent multiple and again combine to pass through the next arc lamp. This will constitute in the main a series circuit, in which, however, incandescent lamps are connected at intervals in multiple. It would therefore be called a **series** of **multiples** or a **series-multiple** circuit. Such a connection is not approved and should never be used on lighting circuits today, for if one of the incandescent lamps should burn out, the others in the multiple would be overloaded through the necessity of carrying the entire current and they would soon burn out also, opening the main line. Figure 39 illustrates a series-multiple connection of batteries which are occasionally connected in this manner. Inequalities of voltage will be smoothed out in such a connection better than in a multiple-series connection. However, the latter connection (multiple-series) is the most commonly used both for lamps and for batteries.

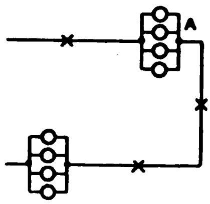


FIG. 38.—Series-multiple connection of lamps.

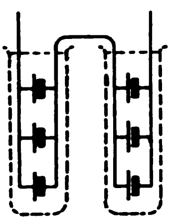


FIG 39.—Series-multiple connection of batteries.

The rule for the combined resistance of either a series-multiple or a multiple-series arrangement of batteries or lamps is as follows: The combined resistance is equal to the resistance of one unit multiplied by the number in series and divided by the number in parallel.

Thus

$$R = \frac{r \times s}{p}.$$

s = number of units in series.
p = number of units in parallel.
r = resistance of one unit.
R = resistance of combination.

Example: Suppose in Fig. 36 there are 10 incandescent lamps of 200 ohms each, connected as shown. What is their combined resistance?

$$\frac{r \times s}{p} = R,$$

Substituting

$$\frac{200 \times 5}{2} = 500 \text{ ohms, combined resistance.}$$

The potential difference generated by a cell of battery or a generator is absorbed in the circuit to which it is connected, and of which it is a part. Some of this e.m.f. is lost within the source, and part is lost externally in the load. Consider a dry cell (B, Fig. 40). A voltmeter connected to its terminals will indicate

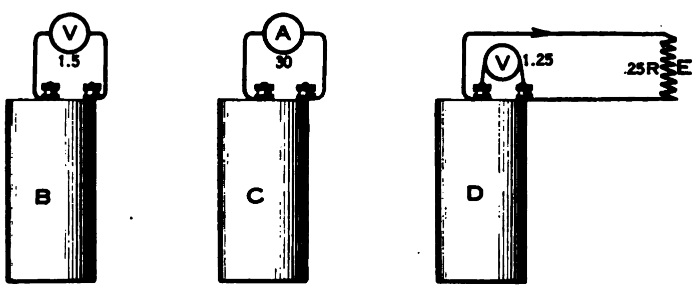


FIG. 40.

1.5 volts. If an ammeter is connected across its terminals, as in C, the maximum current which it will deliver on short circuit may be as high as 30 amperes.

The total resistance of a circuit will be found by applying Ohm's law, thus: $R = \frac{E}{I} = \frac{1.5}{30} = 0.05$ ohm. As the resitsance

of the external circuit in amperes is practically nothing, this entire resistance, 0.05 ohm, may be taken as the internal resistance of the cell.

Now let this cell be connected in series with an external resistance, adjusted to allow a current of 5 amperes to flow, as in *D*. A part of the e.m.f. generated will be absorbed in overcoming the internal resistance of the cell. This amount may be found by calculation, thus:

$E = I \times R = 5 \times 0.05 = 0.25$ volts drop. The delivered voltage will now be less than the generated voltage by the amount of this internal loss. Thus, $1.5 - 0.25 = 1.25$ volts delivered This is what the voltmeter will show when the cell is delivering 5 amperes. To compute the total resistance which will be required in the circuit to allow 5 amperes to flow, $R = \frac{E}{I} = \frac{1.5}{5} =$ 0.3 ohm. As the total resistance of the circuit includes the internal resistance of the cell and the external resistance connected thereto, subtracting the internal resistance from the total, gives the external resistance. Thus, $0.3 - 0.05 = 0.25$ ohm. The delivered voltage of 1.25 is absorbed by this resistance as may be proved, thus, $I \times R = E = 5 \times 0.25 = 1.25$ volts external drop.

The distribution of potentials in a lighting circuit connected to a generator may be better understood by a consideration of Fig. 41. Here, a generator, *G*, having an internal resistance in its

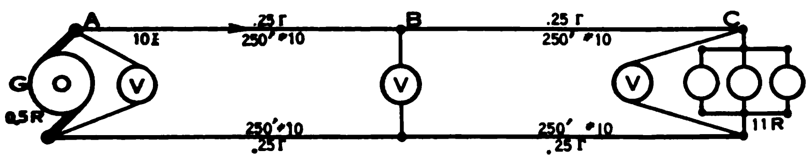


FIG. 41.

armature of 0.5 ohm, is connected through a circuit composed of a total length of 1,000 feet of No. 10 wire having a resistance of 1 ohm, with a lamp bank at *C*, having a resistance of 11 ohms. Let it be required to find the voltage necessary to force 10 amperes through the circuit.

$E = I \times R$, but *R* must include the entire resistance. This resistance is made up of three parts: First, the internal resistance

of the generator; second, the resistance of the line; third, the resistance of the lamp load, thus,

$$E = I \times (R' + R'' + R''') = 10 \times (0.5 + 1 + 11) = 10 \times 12.5 = 125 \text{ volts.}$$

This is the e.m.f. which must be generated by G. Next, let it be required to find the delivered voltage at the points A, B and C. The 10 amperes on its way through the armature of G will encounter the internal resistance. There will be a drop in potential from 125 volts generated, therefore, by the time the current reaches the brushes. The amount of voltage thus lost is $I \times R = E = 10 \times 0.5 = 5$ volts. The voltmeter, V, connected across A will therefore indicate $125 - 5 = 120$ volts. At the point B, half-way between A and C, the current will have passed through the resistance of one-fourth of the 1,000 total feet of No. 10 wire and, returning by the lower wire, it passes through another one-fourth of the total line resistance. The 10 amperes, therefore, encounters the resistance of ½ ohm in the line circuit at the point B. The drop to this point will, therefore, be due to one-half ohm internal resistance in the generator and ½ ohm line resistance, making a total of one ohm. $I \times R = E = 10 \times 1 = 10$ volts lost. The voltmeter at B will therefore indicate 125 volts generated − 10 volts lost, = 115 volts. At the point C, the current will have passed through the entire 1,000 feet of the line, encountering a resistance of ohm in addition to the ½ ohm resistance in the generator. $I \times R = E$. The drop to this point will therefore be $10 \times 1.5 = 15$ volts. The pressure at C will therefore be 125 volts generated − 15 volts lost, equals 110 volts. This pressure of 110 volts which is applied to the lamps is required and absorbed by each and every one connected in multiple. The 125 volts generated are thus distributed in the following ways: 5 volts are lost in the generator armature; 10 volts are lost in the connecting line; 110 volts are lost in the lamp load.

Next consider the conditions in a circuit supplying power to a railway line. Here, generator G, Fig. 42, delivers 600 volts at its terminals and supplies 200 amperes in all to three trolley cars, located as shown in the figure. Car A is one mile from the generating plant; car B is 3 miles, and car C is 4 miles away. The current is carried out over a trolley wire whose resistance is 0.16 ohm per mile and returns through the track circuit, the resistance

of which is 0.04 ohm per mile. Car A takes 80 amperes, car B 50 amperes, and car C 70 amperes.

Let it be required to determine the voltage delivered to each car. As all of the cars are in multiple the current drawn from the generator over the trolley wire to the point D returning over the rail from the point E must be the sum of all the currents for the three cars. This is 200 amperes. The drop in potential from the generator terminals to the first car will therefore be due to the resistance of the trolley and track circuits, each of which is one mile long.

As the resistance of the trolley wire is 0.16 ohm per mile and the track 0.04 ohm per mile, the combined resistance per mile will be 0.2 ohm. The fall in potential is always found from the formula $I \times R = E$ volts, where I is the current in that particular

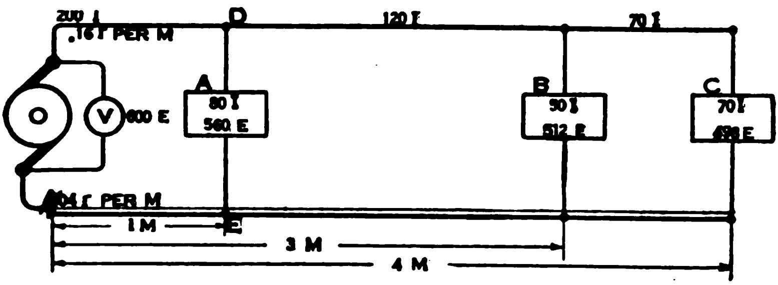


FIG. 42.

circuit and R is the resistance of the circuit. In this instance the "drop" or "fall of potential" will be 200 amperes multiplied by 0.2 ohm, which is 40 volts. This is the amount of loss in the trolley wire and track to car A. The voltage which reaches this car will then be the 600 volts delivered by the generator minus the 40 volts lost in the circuit, or 560 volts.

The drop from this point to car B will be due to the current drawn by the second and third cars multiplied by the resistance of the circuit through which this current flows. As this distance is 2 miles beyond D, the total resistance will be twice the resistance of one mile of circuit. Thus $2 \times 0.2 = 0.4$ ohm. The current passing through this section will be the sum of 50 amperes for car B and 70 amperes for car C, or 120 amperes. The drop in potential will be. $I \times R = E = 120 \times 0.4 = 48$ volts. As the voltage at car A was 560, the circuit may now be considered as though a

generator were placed at D delivering 560 volts. Therefore the voltage at the second car will be 560 − 48 volts = 512 volts.

The drop in potential to the third car will be found by multiplying the current drawn by that car by the resistance of the circuit through which that current flows. As the distance from car B to car C is one mile, the circuit resistance of trolley and track will be 0.2 ohm. The current, as stated, is 70 amperes. The drop will therefore be $I \times R = E = 70 \times 0.2 = 14$ volts. The voltage delivered at car C will therefore be 512 volts − 14 volts = 498 volts.

SECTION II — CHAPTER III

UNITS AND DEFINITIONS

LAWS GOVERNING SIMPLE ELECTRICAL CURRENTS

1. Define a series circuit. Sketch.
2. Define a branch circuit. Sketch. Define a divided circuit. Sketch.
3. Define a parallel circuit. Sketch. Define a multiple circuit. Sketch.
4. Define a shunt circuit. Sketch.
5. Define a short circuit. Sketch.
6. Give a rule for the combined resistance of a series circuit. What is the combined resistance of 50, 100, 10, 40 and 60 ohms in series?
7. Give rule for the combined resistance of two unequal resistances in multiple. What is the combined resistance of 40, and 60 ohms in multiple?
8. Give rule for the combined resistance of any number of equal resistances in multiple. What is the combined resistance of 10 lamps in multiple if each has a resistance of 110 ohms?
9. Give rule for the portion of the total current which is passed by the different branches of a multiple circuit composed of unequal resistances. A current of 30 amperes enters a multiple circuit consisting of 3 branches. The separate resistances are 6, 10 and 15 ohms. How much current does each branch get?
10. What is the unit of conductance? What is its relation to the unit of resistance?
11. Give rule for the combined resistance of any number of unequal resistances in multiple. What is the combined resistance of 50, 30, 20 and 10 ohms in multiple?
12. A cell of battery generates 1.5 volts and has an internal resistance of 0.1 ohms. How much resistance must be inserted in series with this cell externally in order that a current of 3 amperes may flow? With this current circulating, what will be the voltage delivered by the cell?
13. A generator having an internal armature resistance of 0.1 ohm is connected to a lamp bank having a resistance of 10 ohms through two wires, each of which has a resistance of 0.2 ohm. How many volts must the generator produce in order to deliver 10 amperes through the lamps? With this current flowing what will be the voltage delivered at the brushes of the generator?

How much voltage will the lamps receive? What is the "drop" in each of the two wires between the generator and the lamps?

14. Calculate the amount of resistance that must be placed in series with a 110-volt, 5-ampere motor to run it on a 220-volt circuit.

15. How much resistance must be placed in shunt with a 10-ampere, 110-volt motor in order that it may operate properly on a 220-volt circuit if it is connected in series with a resistance of 10 ohms?

16. Define a multiple-series circuit. Sketch such a connection including a number of series of 5 lamps each.

17. Define a series-multiple circuit. Sketch such a connection consisting of a number of cells of battery.

18. Give rule for the combined resistance of a series-multiple and a multiple-series circuit. Tabulate the meaning of each letter used.

19. Given, a multiple-series connected battery consisting of 4 cells in series and 4 sets in multiple. The internal resistance of each cell is 0.05 ohm and its open circuit voltage is 1.50. The battery is connected in series with an external resistance of 0.9 ohm: (*a*) What is the internal resistance of the battery? (*b*) What is the total open-circuit voltage of the battery? (*c*) What current flows through the external resistance? (*d*) What is the total voltage loss within the battery? (*e*) What is the drop in potential across the external resistance?

20. A multiple-series circuit of twenty, 40-watt, 110-volt Mazda lamps is connected up on a street car. There are 5 lamps in series and 4 sets in multiple: (*a*) What is the combined resistance of the multiple-series? (*b*) What is the total current absorbed by the lamps? (*c*) How much current does each lamp get? (*d*) What is the total power in watts?

21. Sketch a multiple-series circuit consisting of forty, 110-volt Tungsten lamps. Indicate how many lamps must be placed in series and how many sets in multiple in order that the total resistance of the multiple-series shall be equal to the resistance of one lamp.

22. A resistance of 100 ohms is connected in multiple with another resistance of 120 ohms. These two are connected in series with a third resistance of 150 ohms. (*a*) What is the combined resistance of the three? (*b*) How much current will 200 volts deliver through the circuit? (*c*) How much current will the 100-ohm resistance get? (*d*) How much current will the 120-ohm resistance get? (*e*) What will be the drop in potential across the two resistances in multiple? (*f*) What will be the drop in potential across the 150-ohm resistance?

23. Fifty arc lamps of 8 ohms resistance each are connected in series and are supplied with a current of 4½ amperes through a line having a total resistance of 10 ohms from a generator having an internal resistance of 4 ohms. (*a*) What is the total voltage produced by the generator? (*b*) What is the voltage delivered at the generator terminals? (*c*) What is the drop in potential across each lamp?

24. A certain circuit consists of 4 ohms, 5 ohms, 3 ohms and 2 ohms connected in series. (*a*) What will be the voltage required to force a current of 10 amperes through the circuit? (*b*) What will be the drop in potential across each of the resistances in series?

25. A certain circuit consists of 4 ohms, 5 ohms, 2 ohms and 10 ohms in parallel. A pressure of 100 volts is applied to the multiple. (*a*) What is the current in each branch? (*b*) What is the voltage on each branch (neglecting the resistance of line wires)? (*c*) What is the total current supplied by the source?

26. A generator supplies 550 volts to a trolley wire. Three cars are spaced one mile apart on the line. The first car is one mile out from the station and requires 50 amperes; the second car is two miles out and requires 40 amperes; the third car is three miles out and requires 60 amperes. The trolley wire has a resistance of 0.4 ohm per mile. The track by which the current returns to the station has a resistance of 0.035 ohm per mile. (*a*) Find the difference of potential applied to each car. (*b*) Find the total voltage lost in the trolley wire and rail return.

SECTION III CHAPTER I

CURRENT ELECTRICITY

NATURE OF ELECTRICAL CURRENTS

It has already been noticed that electrical charges will travel through a conducting substance wherever such a path is provided. If charges could be supplied as rapidly as they travel away through the conductor, a continuous current would be produced. Such a current will always be established in a conducting circuit if the terminals of the circuit are kept at different electrical potentials. In a similar manner a current of heat can be made to flow through a bar of metal if the ends are kept at different temperatures.

Some doubt exists as to the actual direction in which an electrical current flows. It is convenient to regard it as flowing from positive to negative. In order that a continuous flow may be maintained, a complete circuit must be provided. Fig. 43 illustrates the flow of water in a pipe corresponding to the

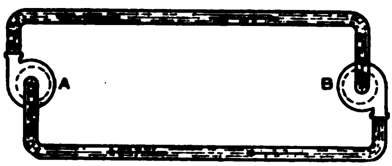


FIG. 43.

flow of an electrical current A rotary pump, A, forces water upward and to the right through the upper pipe and downward through the water motor, B, and thence back through the lower pipe. The pump, A, produces a positive pressure in the upper pipe and a suction in the lower pipe. Electrically, it would be said that a generator produces a positive pressure at the upper terminal and a negative pressure at its lower terminal. There is a **difference in pressure** between the two terminals of the pump and there is a **difference of potential** between the two terminals of a dynamo. So long as this **difference** of potential or **difference** of pressure is maintained, a current of water or of electricity will flow if a conducting path is provided. It is evident from the diagram that the flow of water takes place

simultaneously in all parts of the circuit. An electrical circuit is supposed to be filled with ether which is capable of vibration, just as the water pipe is filled with water. Assuming water to be practically incompressible the motor at B would begin to move at the same instant that the water in the pump A was set in motion. Similarly, an electric current is established in all parts of a circuit at the same instant.

An alternating current is one which alternates in direction, flowing first one way and then the other. Fig. 44 illustrates the corresponding analogy for an alternating current. If the

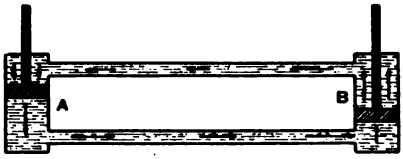


FIG. 44.

pump, A, Fig. 44, has its piston moved up and down, it is evident that it will cause the water to flow first in one direction and then in the other, in the two pipes connecting it with the duplicate apparatus at B. When the piston at A is forced downward, a positive pressure is produced in the lower pipe and a negative pressure in the upper pipe. This would cause the piston at B to move upward. When A stops B will stop. When the piston at A is moved upward, the piston at B will move downward. The water in the two pipes instead of flowing continuously in one direction, as in Fig. 43, will alternate in direction with a frequency depending upon the impulses applied to the piston at A.

The discovery of electrical currents is due to Galvani, a physician at Bologna who in 1786 made a number of important observations upon the convulsive motions produced by electrical discharges through a frog's leg. He found that it was not necessary to employ an electrical machine to produce these effects and that if two dissimilar metals, such as iron and copper, were placed in contact with each other and then brought in contact with a muscle and a nerve respectively, a convulsive contraction would take place. Galvani thought that this was due to electricity generated by the frog's leg. It was conclusively proved by

Volta, a professor in the University of Pavia, that the electricity resulted, not from the frog's leg but from the contact of dissimilar metals.

Whenever two metals are placed in contact with one another in the air, one becomes positive and the other negative, although the charges are very feeble. Volta proved this in various ways. One of the proofs consisted of a voltaic pile, made up of a pair of discs of zinc and copper in contact with one another, upon which was placed a disc of felt moistened with vinegar or dilute acid. Then another pair of discs of zinc and copper, surmounted by another disc of felt, was added, until a hundred or more couples were thus stacked. Such a pile is capable of giving a very powerful shock if the top and bottom discs are connected through metal wires to the hands. Shocks may be obtained repeatedly so long as the felt remains moist. When two dissimilar metals are placed in contact, one becomes positively electrified and the other negatively electrified to a slight extent. Thus, there is a difference of potential between them. When a number of these pairs are connected in series with moist conductors between the successive pairs, the difference of potential between the first zinc and the last copper disc is increased in proportion to the number of pairs, as all of the successive differences of potential are added together.

Consider a small voltaic cell, named in honor of Volta, illustrated in Fig. 45. Here a plate of copper and a plate of zinc are immersed in a dilute sulphuric acid solution. If these two plates are connected together by a wire, a continuous flow of electricity will take place. As the current flows, it is found that the zinc plate wastes away, in fact furnishes the energy necessary to drive the current through the circuit. Zinc possesses potential energy. If set on fire, when surrounded with oxygen, it will burn as a fuel. In the voltaic cell, however, which may be regarded as a chemical furnace, the energy of the zinc instead of being transformed into heat is transformed into electrical energy. The copper plate is not involved in any chemical action, but may be regarded simply as a hand which is let down into the cell to pick up the current derived from the zinc, which

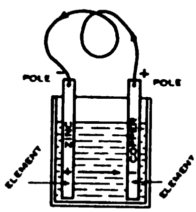


FIG. 45.—Elementary Voltaic cell.

furnishes the energy necessary to drive it through the circuit. The zinc is trying to dissolve and throw a current across to the copper, while the copper is trying less powerfully to dissolve and throw a current across to the zinc. The zinc itself is about 1.86 volts higher in potential than the surrounding oxidizing media, while the copper is only 0.81 of a volt higher, having a less tendency to oxidize. There is, therefore, a difference of 1.05 volts between the zinc and the copper, as illustrated in Fig. 46.

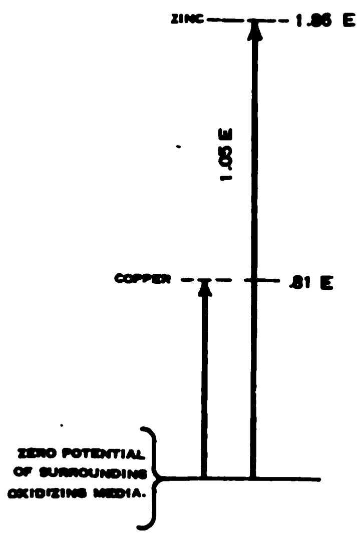


FIG. 46.

This difference of potential can produce no current as long as there is no metallic circuit. If the two plates are connected by a wire, however, there is a rush of current through the acid from the zinc which is at high potential to the copper which is relatively at a lower potential. This current returns through the wire from copper to zinc. A small part of the zinc is at the same time dissolved away. The zinc parts with its latent energy as its atoms combine with the acid. The minute charges possessed by the zinc follow each other in such continuous streams that a current of electricity is established. The energy given up by the zinc is expended in forcing the current through the circuit. The current is supposed to start at the surface of the zinc. The zinc is designated as the **positive element.** The copper is the **negative element** because its potential is relatively lower than the zinc. But the current leaves the cell by the copper terminal, hence this is called the **positive pole.** The current returns from the external circuit to the zinc, which is relatively negative. This zinc terminal is therefore called the **negative pole.** It will be observed that the **positive element** constitutes the **negative pole** and the **negative element** constitutes the **positive pole** in a voltaic cell.

The difference of potential between the two elements is really a measure of the difference of their tendencies to oxidize.

Although an electric current is invisible, four effects are produced whenever a current circulates through a conducting path. Whenever it passes through a wire, heat will be generated in the wire, and a magnetic effect will be present about the wire. Whenever it passes through water or other conducting solutions, they will be decomposed, that is, resolved into their constituent parts. If it flows through the human body it produces certain sensations. An electrical current then is capable of producing four effects; namely, thermal, magnetic, chemical, and physiological. The physiological effect, however, is probably the result of chemical action.

If a number of small voltaic cells are connected together in series, the zinc plate of one being connected to the copper plate of the next, and so on throughout, the difference in potential between the extreme terminals of the series will be equal to the sum of the separate differences of potential. The volume of current delivered, however, on short circuit, would not be increased because the additional cells would offer an increase in resistance as great as the increased difference in potential. Single cells connected in series are illustrated in Fig. 47, where the short, thick bar represents the zinc and the long, thin bar the carbon, copper or other positive terminal of a single cell. When three cells are thus connected in series, the difference of potential, or the pressure, or the electro-motive-force is equal to the sum of the electro-motive-forces of the three cells. In a similar way, if three tanks of water, *A*, *B* and *C*, Fig. 48, are placed on top of one another, the pressure will be proportional to the height of the three tanks. Or it will be three times as great as if one were

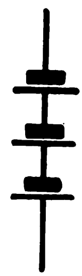


FIG. 47.

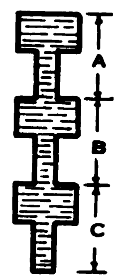
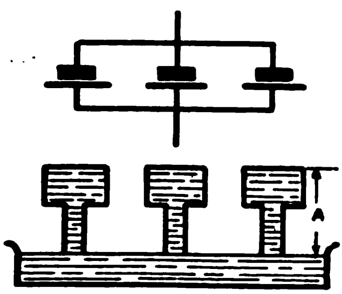


FIG. 48.



FIGS. 49 and 50.

employed. If the three cells are connected in multiple as shown in Fig. 49, the electro-motive-force will be equal to the pressure of one cell only, but the volume of current will be three times as great as in Fig. 47. The reason may be found in the corresponding analogy of water tanks illustrated in Fig. 50, where the total pressure between the top and the bottom of the tanks will be dependent upon the height of the water in the tanks, and as they are all at the same level, the pressure, A, will be simply that of one tank. As the three tanks feed through separate pipes into the reservoir, however, the volume will be three times as great as in Fig. 48.

SECTION III — CHAPTER I

CURRENT ELECTRICITY

NATURE OF ELECTRICAL CURRENTS

1. State clearly the modern conception of an electrical current.
2. Distinguish between electrical charges and electrical currents.
3. In what various ways do static electricity and current electricity differ from each other?
4. Explain by means of the analogy of a water pipe the difference between direct and alternating currents.
5. What were the discoveries of Galvani and Volta?
6. Give a proof of the fact that charges are produced by the contact of dissimilar materials.
7. Explain the construction of a voltaic pile.
8. Explain in detail the action of a simple voltaic cell employing plates of copper and zinc and a solution of dilute sulphuric acid.
9. What governs the voltage of a cell?
10. What are the various factors which determine the current delivered by a voltaic cell?
11. Distinguish between the positive and negative elements and the positive and negative poles in a voltaic cell. Sketch a copper and zinc cell and mark the poles and elements.
12. Sketch a series circuit including five voltaic cells. If each cell delivers an open-circuit e.m.f. of 1.5 volts and a short-circuit current of 20 amperes, what will be the open circuit voltage of the series and the short-circuit current of the series.
13. Sketch a multiple connection of five voltaic cells. If each cell furnishes an open-circuit e.m.f. voltage of 1.5 volts and a short-circuit current of 20 amperes, what will be the open circuit voltage and the short-circuit current of the multiple?

CURRENT ELECTRICITY

CHEMICAL ACTIONS IN CELLS

All substances may be classified as either elemental or compound. An elemental substance is one that cannot be subdivided by any known means into two or more essentially different substances. A compound substance is one that can be so divided.

A **molecule** is the smallest particle of matter that can exist by itself, apart from other particles. Most molecules consist of two or more atoms. An atom is the smallest particle of matter that can be obtained by chemically subdividing the molecule of a compound.

A **physical change** is one that does not affect the composition of the molecule. A chemical change is one that does affect the composition of the molecule.

Sulphuric acid is a **compound** substance consisting of seven atoms. The chemical symbol is H_2SO_4. A molecule of sulphuric acid consists of 2 atoms of hydrogen, 1 atom of sulphur and 4 atoms of oxygen. The smallest particle of sulphuric acid which can be obtained and still retain the identity of the substance, is a molecule. If this be subdivided, from it can be obtained hydrogen, sulphur and oxygen, which are all elemental substances and radically different.

Substances may be mingled together in every conceivable proportion without any chemical combination. Such a mingling is called a mixture. Aluminum-bronze and nickel-steel are mixtures. Elemental substances may unite in certain unvarying proportions to form substances that are entirely different. These are called compounds. Thus two atoms of hydrogen and one atom of oxygen may unite to form water, which is a compound.

Whenever a current passes through a voltaic cell, chemical changes are produced in the solution. The solution must be capable of attacking at least one of the elements and one element should be readily oxidized; the other element should be practically non-oxidizable. Zinc is highly electro-positive and is readily oxidized, and is therefore employed in practically

all voltaic cells. Among the electro-negative substances employed are copper, silver, gold, platinum and carbon. The last three of these are practically non-oxidizable in the presence of any single acid. It is difficult to determine whether the electrical current that is produced in the voltaic cell is due to the chemical action, or whether the chemical action is due to the electrical current. One thing is certain, that both occur simultaneously in the cell.

If a piece of chemically pure zinc is dipped into dilute sulphuric acid, it is not affected by the liquid. But commercial zinc is not pure and the acid will dissolve it, a large quantity of hydrogen gas bubbles being liberated at the surface of the metal. The chemical reaction by which the zinc combines with the acid liberating hydrogen is expressed as follows:

$$Zn + H_2SO_4 = ZnSO_4 + H_2$$

Zinc and Sulphuric Acid produce Zinc Sulphate and Hydrogen. The sulphate of zinc produced in this reaction remains in the liquid.

If a plate of pure zinc and a plate of some less oxidizable metal, or better yet, a plate of carbon, are immersed in a solution of dilute sulphuric acid, no appreciable chemical action will occur until the circuit is closed either by a wire or by bringing the plates in contact. As soon as the circuit is completed a current will flow and the chemical action begins simultaneously. The solution is broken up into its constituent atoms. The evolution of the hydrogen gas bubbles which takes place, however, does not occur at the surface of the zinc nor in the solution, but at the surface of the carbon plate. This apparent transferring of the hydrogen through the solution is quite remarkable. It is supposed that an interchange of atoms occurs on the part of the molecules and that the hydrogen atoms evolved at the surface of the zinc are handed through a chain of molecules and are not actually liberated until they reach the carbon plate. As long as the current flows, the chemical action continues. The zinc is dissolved in exact proportion to the strength of the current and the time which it flows. It dissolves into the solution with which it combines to form zinc sulphate. The quantity of hydrogen liberated is proportional to the amount of zinc dissolved and to the current. After the acid has dissolved all the

zinc that it is possible to take up, it is said to be "killed." It has been turned into a solution of sulphate of zinc. The current will then cease to flow when the zinc has been completely dissolved or when the acid has been killed.

Local Action

In order that a battery may be economical it is desirable that there should be no chemical action, and no wasting away of the zinc, except when the circuit is closed. Commercial zinc, however, on account of the impurities which it contains, is attacked as soon as it is put into acid solution and wastes away more or less even though the main battery circuit is open. This wasting away of the zinc on open circuit is called **local action.** It is supposed to be caused as follows: Commercial zinc contains such impurities as iron and arsenic, as well as other metals. If there be a particle of iron on the surface of the zinc in contact with it and the acid, it will form a small voltaic couple on short-circuit, Fig. 51. The difference of potential between these two metals will start a current which will flow from the zinc into the solution and thence to the impurity on the surface of the zinc, returning through the zinc to the solution again. The zinc will thus be attacked and will waste away by this local current just as though it were a useful current flowing in an external circuit. When the surface of the zinc is covered with myriads of these impurities, local action causes a rapid and continual wasting away of the zinc. This accounts for the fact that a piece of commercial zinc is at once attacked as soon as it is placed by itself in an acid bath. **The remedy for local action is to amalgamate the zinc with mercury.** This is usually accomplished by cleaning the surface of the zinc with acid and then placing a few drops of mercury upon its surface, after which the mercury is rubbed over the zinc with a piece of cloth. The mercury unites with the zinc and forms an amalgam which presents a bright, polished surface. It is supposed that this amalgamation prevents local action by loosening the particles of iron and other impurities, allowing

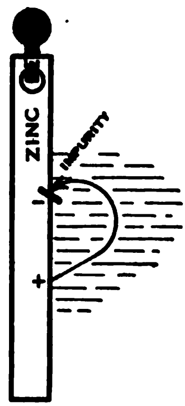


FIG. 51.—Illustrating local action.

them to float up to the surface and thus preventing the local current. As the zinc is consumed the liberated mercury continues to unite with portions of zinc and is not acted upon to any extent by the acid. Another method of thoroughly amalgamating zincs is to add about 4% of mercury to the zinc while in a molten mass. The resulting rod will last much longer in the acid.

Polarization

The bubbles of hydrogen gas which are liberated at the surface of the carbon plate adhere to it in great numbers and form a film over its surface. The surface will gradually be covered by this gas until the whole plate is enveloped. Now hydrogen possesses a high resistance, is highly electro-positive and is nearly as oxidizable as zinc itself. The result of the formation of this film upon the surface of the carbon will reduce the output of the cell in two ways. First, the increased resistance causes a reduction in the current. Second, the electro-positive hydrogen tries to dissolve and throw a current in the other direction from the carbon plate to the zinc. **The establishment of this counter electro-motive-force is known as polarization.** Unless means are taken to prevent it, polarization may in a short time practically stop the entire output of a cell.

Depolarizers

Various means have been proposed for remedying or preventing polarization. These may be classified as mechanical, chemical and electro-chemical.

First: If the surface of the plate is made rough, the hydrogen bubbles adhere rather feebly to it and readily break away from it and float up to the surface. If air is blown into the solution or the solution is agitated in any other way, the gas bubbles are broken. These methods, however, only partially remedy the difficulty and are not practical.

Second: The commonest method is to add to the solution an oxidizing acid which will destroy the hydrogen bubbles as rapidly as they are generated. As a result the increased internal resistance and the opposing electro-motive-force are both prevented.

Chemical depolarizers may be divided into two classes, liquid and solid. Liquid depolarizers consist of some chemical which is dissolved in the solution in which the negative element is

placed. In this solution the negative element is placed. The most commonly used chemicals are nitric acid, chromic acid, bichromate of potash, bichromate of soda and nitrate of potash.

Among the solid chemical depolarizers are black oxide of manganese, oxide of copper, peroxide of lead, and red lead. These materials are not soluble but must be held up to the cathode (negative element) in some way. All of these depolarizers abound in oxygen. When a current passes through the solution and evolves hydrogen at the cathode, it at the same time decomposes the depolarizer and evolves therefrom oxygen. The current causes the oxygen and the hydrogen to combine, forming water. Thus the development of the film of hydrogen upon the cathode is prevented.

Liquid chemical depolarizers act very quickly, causing the hydrogen to be attacked as rapidly as it is formed. Solid chemical depolarizers operate very slowly. They allow the hydrogen to be formed and if a sufficient time elapses thereafter, they will slowly give off oxygen which will attack the hydrogen and form water. Or, if the current is very small, the solid depolarizers may give off oxygen as rapidly as the hydrogen is evolved.

One of the best solutions for producing a large output is **electropion fluid,** which is made as follows: Dissolve one pound of bichromate of potash in one gallon of hot water. When cool, add slowly one quart of chemically pure sulphuric acid. When cold the solution is ready for use. In making solutions of this character, the acid should always be poured into the solution. Never pour the solution on to an acid and thereby confine the acid underneath, as this may cause an explosion.

With reference to the number of solutions which a cell contains, primary batteries may be classified as single-fluid cells and two-fluid cells. A single-fluid cell is one that contains but one solution. If this is weak, the zinc may remain in it constantly, but if it is strong, the zinc should be withdrawn when the cell is not in use. In the latter case the cell is designated as a "plunge" battery. In two-fluid cells the zinc remains in a weak solution constantly. If a liquid depolarizer is employed, the cathode is mounted in a strong solution of the depolarizer, contained in a porous cup which allows moist contact between the weak solution in which the zinc is mounted, but prevents the powerful depolarizer from coming in direct contact with the zinc.

Third: By the employment of a porous cup to separate the elements and the solutions in which they are mounted from each other, it is possible to so arrange things that a solid metal, such as copper, may be liberated at the negative plate in place of hydrogen bubbles. These metallic atoms do not interfere in the least with the passage of the current. This is known as the electro-chemical method of avoiding polarization.

With the electro-chemical method of avoiding polarization, each element is mounted in a solution of its own salt. In all two-fluid cells, the elements and their respective solutions may be separated by a porous partition of paper or unglazed earthenware, or they may be arranged to be separated by gravity, in which case the lighter solution and the element immersed therein rest on top of the heavier solution and its element.

Laws Governing Chemical Actions

The laws governing chemical actions in voltaic cells are as follows:

1. The amount of chemical action in a cell is proportional to the quantity of electricity that passes through it. That is to say, is proportional to the current while it passes. One ampere of current flowing through the cell for one second liberates 0.000010384 gram of hydrogen.

2. The amount of chemical action is equal in each cell of a battery consisting of a number of cells joined in series. That is to say, the same amount of zinc will be dissolved and the same amount of hydrogen liberated in each cell, regardless of the size, whether they be large or small throughout the series.

SECTION III CHAPTER II

CURRENT ELECTRICITY

CHEMICAL ACTIONS IN CELLS

1. Define an elementary substance.
2. Define a compound substance.
3. Define a molecule.
4. Define an atom.
5. What constitutes a physical change in a substance?
6. What constitutes a chemical change in a substance?
7. Distinguish between mixtures and compounds.
8. What is the relation between the production of current in a voltaic cell and the accompanying chemical action?
9. Explain by means of chemical symbols the chemical action that takes place in a voltaic cell containing sulphuric acid solution and zinc and copper elements.
10. Explain "local action" in a voltaic cell. What is its cause and what various remedies may be employed?
11. Explain "polarization" in a voltaic cell. What is it, and what are some of the remedies that may be employed?
12. Explain the mechanical means employed for avoiding polarization in a voltaic cell.
13. Explain the chemical means employed for avoiding polarization in a voltaic cell.
14. Tabulate the solid and liquid chemical depolarizers commonly used. How are they employed?
15. Explain the electro-chemical method of avoiding polarization.

CURRENT ELECTRICITY

PRIMARY BATTERIES

A primary cell should give a constant e.m.f. The e.m.f. is determined by the nature of the materials used and the strength of the solution. The highest e.m.f. practical is that obtained between carbon and zinc with a strong solution of bichromate of potash. This is about 2.1 volts. Such an e.m.f., however, is not constant but falls rapidly. Constancy of e.m.f. is to be preferred to high e.m.f. for cells may be connected in series and thus obtain as high voltage as desired.

In order that the voltage lost in a cell may be low, it should have a low internal resistance. If the plates are large and are placed close together the internal resistance will be low. A cell should be capable of delivering a large and constant current. This will naturally follow if the internal resistance is low and the e.m.f. is high and constant. Here again, however, constancy of current is preferable to a large current if both conditions cannot be complied with, for cells may be connected in multiple to deliver a large current. A cell should be constructed of such materials and in such a way that there will be no consumption or waste on open circuit. That is, local action and deterioration of the solution should be avoided. A cell should be cheap, durable and should not give off corrosive fumes.

Daniell Cell

In the Daniell cell the electro-chemical method of avoiding polarization is employed. This cell is based upon the discovery of Daniell that whenever a current passes from a metal to a solution of its own salt, metallic atoms are dissolved into the solution. On the other hand, if a current is passed from a solution of a metallic salt to a solid conductor immersed therein, metallic atoms are taken out of the solution and deposited on that conductor. Based on this discovery Daniell constructed a cell, Fig. 51, in which a zinc element is placed in a jar in a solution of dilute zinc sulphate or dilute sulphuric acid. In a porous cup is placed a plate of copper in a solution of sulphate of copper. Some additional crystals of copper sulphate are placed in a

pocket in the copper plate or thrown in the bottom of the porous cup. When a current is drawn from the cell the action is as follows: The zinc is attacked by the dilute sulphuric acid and dissolves, forming zinc sulphate. The hydrogen which would ordinarily be evolved from this solution is handed through the porous partition into the copper sulphate solution. The copper sulphate is at the same time broken up. The H_2 unites with the SO_4 portion of the copper sulphate to form sulphuric acid, and a single atom of copper is liberated at the copper plate in place of two atoms of hydrogen. This cell, therefore, does not polarize as there is an exchange of hydrogen atoms for copper atoms at the cathode and these copper atoms which are deposited or plated on the cathode do not interfere with the output of the cell in any way. The cell will therefore deliver a very uniform current and voltage so long as there is a sufficient supply of copper sulphate crystals to produce the necessary chemical combinations. The two sets of actions which take place may be expressed in the following way:

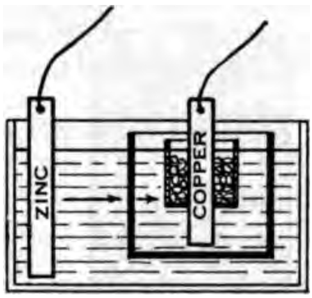


FIG. 52.—Daniell Cell.

$$Zn + H_2SO_4 = ZnSO_4 + H_2$$

Zinc and sulphuric acid produce zinc sulphate and hydrogen.

$$H_2 + Cu\ SO_4 = H_2SO_4 + Cu$$

Hydrogen and copper sulphate produce sulphuric acid and copper.

Gravity Cell

Fig. 53 represents the commercial form of Daniell cell. It is commonly known as the bluestone gravity battery. Instead of separating the solution by a porous partition, gravity is relied upon. The copper is placed in the bottom of the jar with about a pound of copper sulphate crystals. The cell is then filled with water and the zinc hung on the edge of the jar. The insulated lead from the copper terminal is then connected to the zinc binding post and the cell left on short circuit for about 24 hours. There is enough free sulphuric acid in the solution to

attack the zinc. This forms in the upper part of the jar a solution of zinc sulphate and sulphuric acid which is light enough to float on top of the heavier copper sulphate solution, which sinks toward the bottom. The dividing line between these two solutions is called the "blue line" and it rests about half-way between the zinc and the copper. After being short-circuited about 24 hours, the cell may be open-circuited and put to work. It works best when kept on closed circuit about half the time. If it is closed-circuited too long, the blue line sinks; if it is left open-circuited too long, the blue line rises. Experience will enable one to determine the amount of time the cell should be kept on closed circuit to maintain the blue line midway. The cell was formerly used very widely in telegraph work but has been largely replaced by storage batteries and generators for this purpose. It is, however, still employed on local telegraph circuits on railroad lines. It gives an e.m.f. of one volt and a short-circuit current of about one ampere.

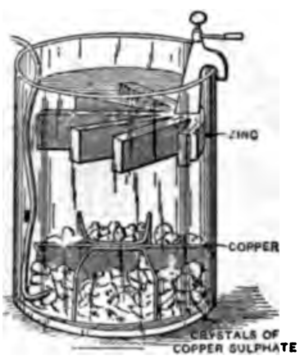


FIG. 53.—Blue-stone gravity cell.

LeClanche Cell

The LeClanche type of cell employs carbon and zinc elements and a solution of salammoniac. Salammoniac is ammonium chloride. This type of battery is built in a great variety of forms and is known by many trade names. Figure 54 shows the internal construction of one popular type, while Fig. 55 shows the

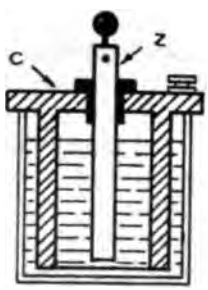


FIG. 54.—Cylindrical LeClanche cell.

FIG. 55.—Outside appearance of LeClanche cell.

actual appearance of the same cell. It contains a carbon cylinder, *C*, slotted to permit the circulation of the solution. The zinc, *Z*, passing through a porcelain bushing is mounted in the center of the cylinder. The charge of salammoniac is four ounces for the ordinary jar holding about one quart. The e.m.f. is 1.4 to 1.5 volts for this carbon cylinder cell, and the short circuit current is from two to eight amperes. This cell and the majority of batteries of this type employ no depolarizer, as the current is drawn for only a brief time—really but a few seconds each day. The large surface of the carbon allows the hydrogen bubbles to form for some time without covering it and they burst before serious polarization sets in. Figure 56 is a type having a lower internal resistance. It is known as the Samson or Hercules battery and employs a fluted carbon cylinder, *C*, around which is placed a cylindrical zinc, *Z*, of large surface. The carbon cylinder is hollow and is filled with black oxide of manganese, *M*, and the hole at the bottom closed with sealing wax.

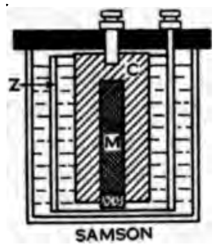


FIG. 56.—Sampson LeClanche Cell.

In the Sampson battery the manganese dioxide gives up its oxygen and slowly depolarizes the cell. This cell will give about 7 or 8 amperes on short-circuit. The location of the black oxide is wrong, however, as it is on the inside instead of the outside of the cylinder. The Samson battery is adapted for annunciator and clock work, while the carbon cylinder battery is used for door-bell work.

Dry Cell

The so-called dry battery is of the LeClanche type, sealed up to prevent slopping. It is not really a dry cell at all, for if it were dry it would give off no energy. The most common form of dry cell consists of a zinc retaining cup 2½″ in diameter and 6″ high. Inside of this is placed a porous partition consisting of two or three layers of blotting paper. The positive pole consists of a carbon cylinder around which is a mixture of

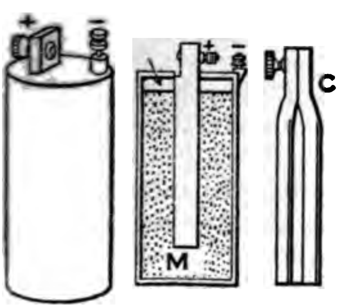


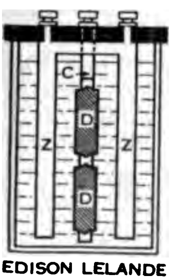
FIG. 57.—LeClanehe Cell.

manganese dioxide, ground coke, salammoniac and zinc chloride. The manganese dioxide acts as the depolarizer. The ground carbon, which is next to the paper, collects the current from the zinc at the periphery of the mixture and conducts it by means of the other carbon particles to the center carbon plug. The salammoniac is the electrolyte while the zinc chloride is used only to improve the life of the cell by reducing local action. The zinc is the most expensive part of the cell. Figure 57 shows the detail construction of the dry cell.

The elements, solution, depolarizer and voltage are all the same in all types of wet and dry LeClanche cells. Dry cells may be used for bell work, operation of annunciators, small motors, automobile ignition and even for small incandescent lamps. The internal resistance of the 2½″ x 6″ cell is so low that it will, when new, frequently furnish from 20 to 30 amperes short-circuit current. The cell polarizes rapidly if a continuous current is drawn, unless the current is very small.

Edison LeLande

The Edison LeLande cell is shown in Fig. 58. It consists of copper, *C*, and zinc, *Z*, elements and a solution of 25% caustic potash. The depolarizer, *D*, is a compressed block of black oxide of copper held in a copper frame, which together constitute the negative element. The e.m.f. is 0.7 volt. The solution is covered with a layer of paraffine oil to keep the air away from the caustic potash, which would cause it to deteriorate. The cell is manufactured in various forms and sizes. Porcelain or enameled steel retaining jars are frequently used. There are usually two zincs, *Z*, one hung on each side of the copper oxide element, *D*, which is mounted in the retaining frame, *C*. As cells of this type have the zinc attacked near the surface of the solution more rapidly than elsewhere, the zincs are purposely made thicker at this point to avoid their being eaten in two. This cell is used for the operation of railway signals.

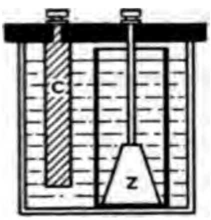


EDISON LELANDE

FIG. 58.—Edison LeLande Cell.

Fuller Cell

The Fuller mercury-bichromate cell is shown in Fig. 59. The elements are carbon, *C*, and zinc, *Z*. The zinc is placed in a porous cup. The solution next to the carbon is bichromate of soda which forms the depolarizer. The porous cup contains water which soon becomes contaminated through the porous cup by contact with the bichromate of soda. In the bottom of the cup and next to the zinc is placed a quantity of mercury. This permits small scraps of zinc to be thrown into the cup, which are automatically connected with the zinc through the puddle of mercury. The mercury diffuses itself over the surface of the zinc which is thus well amalgamated. The e.m. f. is 1.75 volts. The current depends upon the size of the cell. In some forms it is made of from 1 to 3 carbon plates, while in other cells it consists of a cylindrical carbon within which is placed the porous cup. The cell will furnish a large current for a short time. It is used for electro-plating.



FULLER

FIG. 59.—Fuller Cell.

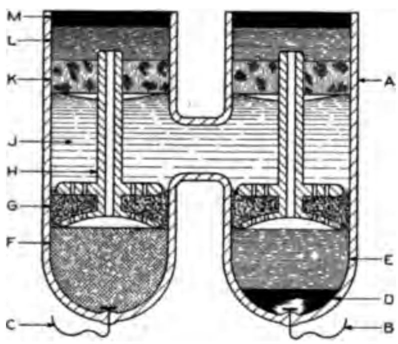


FIG. 60.—Weston Standard Cell.

Courtesy Leeds & Northrup Co.

A–Glass
B–Platinum wire
C–Platinum wire
D–Mercury
E–Mercury sulphate
F–Cadmium amalgam
G–Porous packing
H–Porcelain separator
J–Cadmium sulphate solution
K–Cork
L–Wax
M–Seal

Weston Standard Cell

The Weston cell, Fig. 60, is now used almost exclusively as the standard of e.m.f. It usually consists of a cadmium amalgam covered with crystals of cadmium sulphate, and chemically pure mercury in contact with a paste of mercurous sulphate and cadmium sulphate. The solution is made up of mercurous sulphate and cadmium sulphate. The voltage of this cell is approximately 1.0186 in the saturated type and about 1.0196 in the unsaturated type. Its e.m.f. is practically constant for a wide change in temperature.

SECTION III CHAPTER III

CURRENT ELECTRICITY

PRIMARY BATTERIES

1. What are the requirements for a satisfactory cell?
2. Explain the construction of the Daniell two-fluid cell. Explain in detail the chemical actions that take place during discharge.
3. Explain the construction of the gravity cell. Give elements, solutions, method of avoiding polarization, e.m.f., and kind of work for which it is adapted.
4. Explain the construction of the Leclanche wet type of battery. Give elements, solution, depolarizer, e.m.f. and kind of work for which it is adapted.
5. Explain the construction of the Leclanche dry type of battery. Give elements, solution, depolarizer, e.m.f. and kind of work for which it is adapted.
6. Explain the construction of the Edison Lalande cell. Give elements, solution, depolarizer, e.m.f. and kind of work for which it is adapted.
7. Explain the construction of the Fuller cell. Give elements, solutions, depolarizer, e.m.f. and kind of work for which it is adapted.
8. Explain the Weston standard cell. Give elements, solutions, method of avoiding polarization and the particular object for which this cell is designed.

CURRENT ELECTRICITY

ELECTROLYSIS

Liquids may be divided into three classes. First, those which do not conduct at all, such as oils and turpentine. Second, those which conduct without decomposition, such as mercury and molten metals, which conduct the same as do solid metals. Third, those which are decomposed when conducting, such as dilute acids, solutions of metallic salts and certain fused solid compounds.

It was discovered by Carlisle and Nicholson in 1800 that the passage of a current through water was accompanied by the decomposition of the water. The water was resolved into its

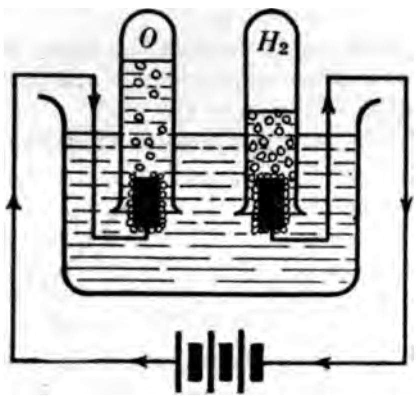


FIG. 61.—Electrolysis of water.

component parts, oxygen and hydrogen. By using an apparatus illustrated in Fig. 61, this experiment may be duplicated. Two test tubes, into the mouths of which project electrodes of platinum, are filled with acidulated water and mounted in a larger vessel with their openings below the surface of the water contained therein. If current from a few cells of battery is now passed from one of these electrodes to the other, the water will be decomposed, the oxygen rising in one tube where the current enters, and replacing in the upper end of this tube, the water which falls. Hydrogen is evolved at the electrode where the

current leaves, and is accumulated in the top of this tube. The volume of oxygen and hydrogen are almost exactly in the ratio of one to two, which is the chemical composition of water. The amount of oxygen, however, is not quite one-half the volume of hydrogen, for two reasons. First, a part of the oxygen is given off in the denser form of ozone, which is slightly soluble in water. Second, a portion is absorbed or occluded by the pores in the platinum. Thus, the volume of hydrogen is slightly more than twice the volume of oxygen. Such an apparatus is known as a **water voltameter.** It is evident that the dividing line between the gas and the solution would indicate the quantity of electricity passing on a scale pasted on the outside of one of the tubes. Now, suppose that the water in the jar and tubes shown in Fig. 61 be replaced with copper sulphate, and the current passed through as before. The current now breaks up the copper sulphate and resolves it into copper and sulphion.

Thus, $CuSO_4 = Cu + SO_4$.

The sulphion now combines with the water which is present in the solution to produce sulphuric acid and oxygen.

Thus, $SO_4 + H_2O = H_2SO_4 + O$.

The oxygen is liberated at the plate where the current enters, while metallic copper is liberated at and deposited upon the plate where the current leaves the solution. The oxygen accumulates in the tube where it is liberated as before, but there is no gas liberated in the tube above the other pole.

Electrolysis

Faraday gave the name **electrolysis** to the process of decomposing a liquid by passing a current through it. Electrolysis means electrical analysis.

The vessel in which the decomposition takes place is called an **electrolytic cell.**

The elements by which connection is made to the external circuit are termed the **electrodes.**

The solution that is decomposed by the passage of the current is termed the **electrolyte.**

The element by which the current enters the electrolytic cell is called the **anode.**

The element by which the current leaves the electrolytic cell is called the **cathode.**

The decomposition of the electrolyte into its constituent parts liberates atoms which Faraday called **ions.** These ions move through the solution as if attracted by the electrodes. Those which are found at the surface of the cathode are called **cations.** Hydrogen gas and the metals are cations. They are electro-positive and are attracted to the cathode. Those ions which are found at the surface of the anode are called **anions.** Anions are electro-negative and move toward the relatively electro-positive anode. Oxygen ions are anions.

If the electrodes of platinum in Fig. 61 be replaced with copper and a solution of copper sulphate be employed, then no gas will

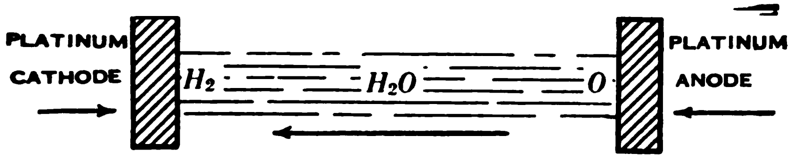


FIG. 62.

be evolved at either of the electrodes, but an atom of copper will be dissolved from the anode where the current enters and an atom of copper will be deposited on the cathode where the current leaves. The anode thus wastes away while the cathode grows. The solution does not change its character or density and no gas is liberated. Such an arrangement is called a copper voltameter. As one ampere of current flowing through such a cell will liberate 0.0003281 gram of copper in one second, it is evident that the product of the total current in amperes flowing and the time in seconds is the quantity of electricity in cou-

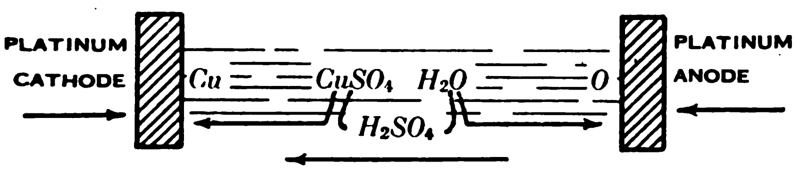


FIG. 63.

lombs and can be estimated accurately by weighing the anode and finding out how much it has lost after a given interval, or by weighing the cathode and calculating how much it has gained.

Fig. 62 illustrates the electrolysis of water with non-oxidizable electrodes. It shows the evolution of oxygen gas at the anode and hydrogen gas at the cathode. Fig. 63 represents

the electrolysis of copper sulphate in a cell with non-oxidizable electrodes. Here oxygen is evolved at the anode as before in gaseous form but metallic copper is evolved and deposited on the platinum cathode and no gas is liberated at that point. The chemical symbols show how the water and the copper sulphate are broken up and recombined to form sulphuric acid during the passage of the current. Fig. 64 represents the electrolysis of copper sulphate with oxidizable electrodes of copper.

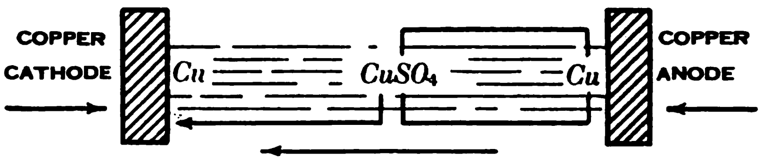


FIG. 64.

Here simultaneously with the decomposition of a molecule of copper sulphate in the vicinity of the anode, one atom of the copper anode passes into the solution to combine with the SO_4 from the copper sulphate molecule, while the atom of copper which this molecule previously contained is at the same time handed through the solution until it is finally liberated and deposited in metallic form upon the copper cathode. In this case no gas will be evolved at either electtode but there will be a continuous migration of metallic atoms through the solution from the anode to the cathode. The cathode gains one atom for every one that the anode loses.

Voltameters of copper, silver and zinc have been constructed. The first meter for registering the consumption of current used by a consumer on an electric light circuit was a zinc voltameter devised by Edison.

Laws of Electrolysis

There are three quantitative laws of electrolysis:

First: The amount of chemical action is the same in all parts of a circuit. If several electrolytic cells be put in series and a current sent through them, the amount of hydrogen evolved in every case will be the same, even though the cells differ greatly in size.

Second: The amount of ions liberated is proportional to the current. That is to say, two amperes of current will liberate

twice the amount of hydrogen or dissolve twice as much metal from the anode as will one ampere.

Third: The amount of ions liberated is equal to the current multiplied by the electro-chemical equivalent of a substance multiplied by the time.

This is expressed by the formula:

$$Wt = ZIt.$$

Wt = weight in grams.
Z = electro-chemical equivalent of the substance.
I = current in amperes
t = time in seconds.

Knowing any three quantities in the above equation it is possible to calculate the fourth. Thus if the weight of metal which it is desired to deposit, the electro-chemical equivalent of that metal and the current are known, it is possible to calculate the time required to deposit that weight with the specified current.

The chemical equivalent of a substance is equal to the atomic weight divided by the valency.

The atomic weight of a substance refers to the weight of one of its atoms compared with an atom of hydrogen. Thus, the atomic weight of copper is 63; that is, its atoms are 63 times as heavy as hydrogen atoms.

The valency of a substance means its value in chemical combinations; that is, the number of hydrogen atoms which it will replace. Thus, in chemical combinations, copper has a valency of two. That is, one atom of copper will replace or is worth two atoms of hydrogen. The quotient obtained by dividing the atomic weight by the valency is termed the chemical equivalent. Therefore, $\frac{63}{2} = 31.5$, which is the chemical equivalent of copper.

The chemical equivalent multiplied by the electro-chemical equivalent of hydrogen equals the electro-chemical equivalent of any particular substance. In other words, the electro-chemical equivalent of a substance is the weight in grams of that substance liberated by the passage of one coulomb of electricity.

The electro-chemical equivalent of hydrogen is 0.000010384.
" " " " " silver " 0.001118.
" " " " " copper " 0.0003281.

SECTION III CHAPTER IV

CURRENT ELECTRICITY

ELECTROLYSES

1. Into what three classes are all liquids divided?
2. Define electrolysis.
3. Define an electrolytic cell.
4. Define the electrodes of a cell.
5. Define the electrolyte of a cell.
6. Define the anode of a cell.
7. Define the cathode of a cell.
8. Define the ions in a cell.
9. Define cations in a cell.
10. Define anions in a cell.
11. Explain in detail the electrolysis of water with platinum electrodes.
12. Explain in detail the electrolysis of copper sulphate with platinum electrodes.
13. Explain in detail the electrolysis of copper sulphate with copper electrodes.
14. Give the first quantitative law of electrolysis.
15. Give the second quantitative law of electrolysis.
16. Give the third quantitative law of electrolysis.
17. What is meant by the "chemical equivalent" of a substance?
18. What is meant by the electro-chemical equivalent of a substance?
19. What is the electro-chemical equivalent of hydrogen?
20. Give the formula for the weight of metal deposited in an electrolytic cell by a given current in a given time. Tabulate the meaning of each letter.
21. How many hours will it take to deposit 100 pounds of copper in an electrolytic cell containing a copper sulphate solution, if the current passing is 100 amperes? (453.6 grams equal one pound).
22. What is the chemical affinity of oxygen and hydrogen in water expressed in terms of e.m.f.?

SECTION III CHAPTER V

CURRENT ELECTRICITY

PRINCIPLES OF SECONDARY CELLS

If a charging current is sent through a Daniell cell in the reverse direction to the normal flow, such a current will dissolve the copper into the sulphuric acid solution, forming sulphate of copper. The same current will take zinc atoms out of the zinc sulphate solution and deposit them upon the zinc plate. This is in accordance with Daniell's discovery that whenever a current flows from a solution of a metallic salt to a metal plate, metallic atoms are plated out of the solution on to the electrode, and whenever the current passes from a metal to a solution capable of attacking it, metallic atoms are dissolved into the solution. In this way the copper is dissolved and the zinc is built up. A Daniell cell can be recharged in this way instead of employing fresh chemicals. The Daniell cell is a connecting link between primary and secondary cells.

If the electrodes in the water voltameter in Fig. 61 were lengthened so as to extend into the space occupied by the gas, it would be found that a difference of potential existed between them. The difference of potential is the measure of the chemical affinity of oxygen and hydrogen for each other. It is necessary to apply at least 1.47 volts to separate these gases from the water. When the e.m.f. which separated them has been withdrawn, the gases tend to recombine with the same e.m.f. Some of the voltage, however, is lost in heat so that practically only about 0.97 volt is available. A battery in which the plates are composed of nothing but oxygen and hydrogen gas may be constructed as shown in Fig. 65. Here two plates of carbon, A and B, are immersed in a dilute sulphuric acid solution. When a charging current from a few cells of battery is passed through the circuit, oxygen is evolved at the surface of the

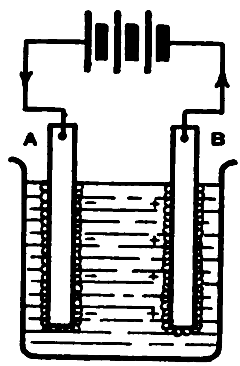


FIG. 65.

plate, A, where it accumulates as a gas film, while hydrogen is precipitated upon plate B. If now the external battery is disconnected, the carbon plates, A and B, which normally have no difference of potential between them, will be found to have a substantial e.m.f. available. The hydrogen gas film on plate B, which is positive, tends to send charges across to the negative oxygen film on the plate A. If these two plates are connected externally, a current will flow. This current will continue so long as there is any hydrogen gas to be attacked by the solution. What really occurs is that the flow of this reverse current develops oxygen at the surface of the hydrogen plate, which combines with it to form water, while hydrogen is evolved at the surface of the oxygen plate. But instead of now forming a film which would polarize the cell, the oxygen on the surface of the plate A acts as a depolarizer, combining with the hydrogen to form water. This is really a storage cell in which energy is stored in the form of work done, in separating oxygen and hydrogen gases from water. The arrangement is not suitable for practical work, however, because the gases would eventually bubble up and escape. Furthermore, the battery would have to be very large in order to accumulate any considerable amount of energy.

In 1860 Planté devised a practical form of storage cell which has been successfully used ever since. Planté sought to find

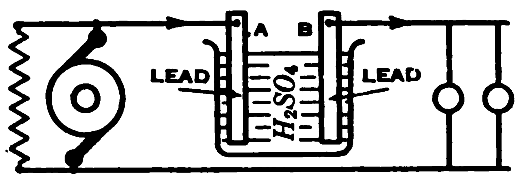


FIG. 66.

some combination of materials in which the energy of the gas battery could be stored in a more compact form. After experimenting with a vast number of materials, he found that the best results were obtained by mounting two plates of plain lead in a dilute solution of sulphuric acid and water. If a charging current is sent from a generator, Fig. 66, through the two lead plates, A and B, mounted in a sulphuric acid solution, oxygen is evolved at the surface of the plate A, and attacks it, forming peroxide

of lead (PbO_2). Hydrogen is evolved at the surface of the plate *B*, where it appears in a gaseous form without attacking the plate. When the generator is disconnected a reverse current will flow if a circuit is provided. This current will start from the positive hydrogen and flow through the acid solution toward the peroxide of lead plate. Upon the flow of this reverse current the peroxide will give up some of its oxygen and thus prevent polarization. After the hydrogen has disappeared, some of the adjacent lead will also be attacked and oxidized by the secondary current. As hydrogen is highly electro-positive, the initial difference of potential between the plates is 2.5 volts. When the hydrogen film has disappeared, the e.m.f. falls to 2.0 volts. The current will continue to flow so long as there is any peroxide of lead on the plate to be reduced. The energy is stored in the peroxide plate. The cell is really a secondary cell.

The term storage battery is inappropriate because the energy stored is in chemical and not electrical form. The actual current which is delivered is entirely distinct from the original charging current. It is caused by the reaction brought about by the chemical work originally done in charging the cell. The peroxide plate is always called positive and the plain lead plate always negative on both charge and discharge.

If the charging current originally sent through this cell is continued beyond a certain point, it involves a waste of energy for there is a limit to the amount of peroxide which can be formed. The peroxide coating seems to cover up the lead plate and prevent the acid from attacking it beyond a limited depth.

Sulphating

If the cell is allowed to rest after it has been charged, "local action" sets in. This is because lead is always positive to its oxides. The peroxide film does not form an absolutely impervious coating over the surface of the lead plate, but allows the acid to come in contact with both. Just as a current flowed from the zinc to the iron impurity imbedded therein, through the conducting solution in which it was immersed in the primary cell, so a current starts from the relatively positive lead and flows through the solution to the relatively negative peroxide. This reduces the peroxide to lead sulphate and attacks the lead base more deeply. In the early stages of "forming" or developing of a lead plate, a limited amount of "local action," otherwise

known as **sulphating,** is advantageous, because the porosity of the plate is increased. It is dangerous, however, if allowed to proceed too far, as the plate may be entirely converted into lead sulphate. Now lead sulphate is an insoluble salt of lead, having no mechanical strength and the plate would eventually fall to pieces for want of stability.

Various schemes have been devised for increasing the surface of the plate presented to the acid. The capacity of a cell depends upon the amount of peroxide developed. The surfaces of the plates are sometimes roughened or pickled in nitric acid to increase the amount of surface.

There is usually one more negative plate than positive plates in a storage cell. They are arranged as shown in Fig. 67. This plan enables both sides of each positive plate containing the active material to be presented to a negative plate, and insures the greatest amount of energy being obtained from the cell on discharge. Also the additional negative plate furnishes an additional mechanical support to the positives.

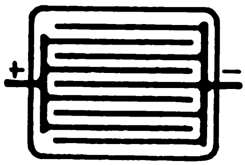


FIG. 67.

Chemical Actions

The chemical actions involved in the charge and discharge of a secondary cell may be explained as follows: When the cell has been assembled and charged for the first time, peroxide of lead, which is of a deep chocolate color, forms on the positive plate or anode. Hydrogen gas forms on the negative plate, or cathode. We now have at the positive plate PbO_2 in contact with H_2SO_4, and at the negative plate Pb in contact with H_2SO_4. During discharge, the molecules rearrange their combinations as follows:

One atom each of PbO_2 and H_2SO_4 in contact therewith, and one atom each of Pb and H_2SO_4 in contact therewith recombine thus:

$$PbO_2 + H_2SO_4 + H_2SO_4 + Pb = PbSO_4 + H_2O + PbSO_4 + H_2O$$

Combining,

$$PbO_2 + 2H_2SO_4 + Pb \; \underset{\longleftarrow \text{Charge}}{\overset{\text{Discharge} \longrightarrow}{=}} \; 2PbSO_4 + 2H_2O.$$

The chemical symbols for lead and its compounds are as follows:

Lead..............................	Pb
Red lead..........................	Pb_3O_4
Peroxide of lead..................	PbO_2
Monoxide of lead..................	PbO
Sulphate of lead..................	$PbSO_4$
Hard sulphate of lead.............	Pb_2SO_5

The above is known as the fundamental equation of the storage battery. If read from left to right it represents the conditions taking place when the battery is being discharged.

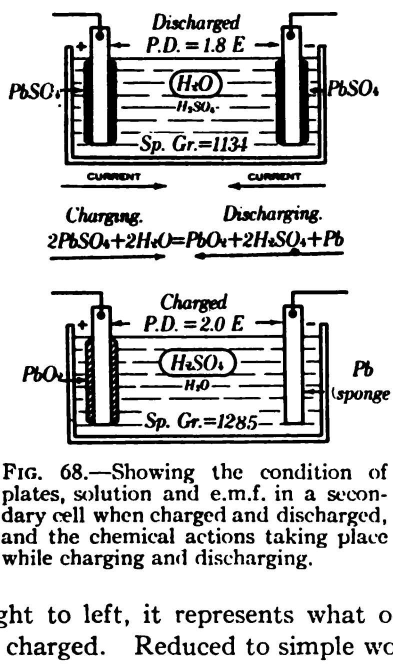


FIG. 68.—Showing the condition of plates, solution and e.m.f. in a secondary cell when charged and discharged, and the chemical actions taking place while charging and discharging.

If read from right to left, it represents what occurs when the battery is being charged. Reduced to simple words, it amounts to saying that when a battery is discharged, one molecule of peroxide of lead and two molecules of sulphuric acid and one molecule of plain lead are converted into two molecules of lead sulphate and two molecules of water. It will be observed that the two plates do not revert to their original condition of plain lead on discharge, but are changed to lead sulphate. Now, when the cell is charged, the two molecules of lead sulphate and the two molecules of water are changed back again into one

molecule of peroxide of lead, two molecules of sulphuric acid and one molecule of plain lead. The plain lead, however, is now quite porous and is known as sponge lead. Thereafter in subsequent charges and discharges the chemical condition represented on the right side of the equation always indicates the battery in its discharged condition, while the expressions on the left side of the equation represent the battery in its charged condition.

Forming

After the sponge lead has been formed on the negative plate and the peroxide on the positive plate during a charge, it is found that when these plates are discharged they will be attacked more deeply by the second and each subsequent charging current. Thus, by repeated charging and discharging of the cell the surface of the plates can be developed to a considerable depth, and the amount of active material increased until a certain maximum has been obtained. This is technically known as **forming** of plates. The process is slow and expensive. It takes several weeks to properly form a battery in this way and then the film of active material is not more than $\frac{1}{32}$d of an inch thick.

SECTION III — CHAPTER V

CURRENT ELECTRICITY

PRINCIPLES OF SECONDARY CELLS

1. Explain in detail what happens to the two elements and the two solutions in a Daniell cell during discharge.

2. Explain in detail what happens to the two elements and the two solutions in the Daniell cell if a charging current is sent through it in the reverse direction to its natural e.m.f.

3. (*a*) Explain the construction of a gas battery.
   (*b*) What are the electrodes?
   (*c*) What are the elements?
   (*d*) What voltage must be employed to charge it?
   (*e*) What is the potential difference available when charged?

4. Explain the construction of the elementary form of Planté secondary cell.

5. (*a*) What is the maximum e.m.f. of a secondary lead cell when first disconnected from a charging circuit?
   (*b*) What is the working e.m.f. of this cell?

6. When a lead cell is charged, which plate is attacked by the acid, and into what form is it changed?

7. What governs the amount of energy which a secondary cell can store?

8. (*a*) What are the polarities of the two plates when charging?
   (*b*) What are the polarities of the two plates when the cell is discharging?
   (*c*) What is the peroxide plate always named?

9. Explain the cause and effect of "local-action" in a secondary cell, if allowed to rest on open circuit after charging?

10. What is the nature of lead sulphate?

11. What are the relative number of positive and negative plates in a cell? Why is this construction adopted?

12. (*a*) State, in chemical symbols, the fundamental equation for a storage battery.
   (*b*) State this equation in words.

13. How is this equation read to express what takes place during charging?

14. How is this equation read to express what takes place during discharge?

15. Show by a sketch, the condition of the plates, solution and available e.m.f. in a discharged secondary cell.

16. Show by a sketch the condition of the plates, solution and available e.m.f. in a charged secondary cell.

17. What is meant by "forming" the plates in a secondary cell?

CURRENT ELECTRICITY

CHEMICAL ACTIONS IN SECONDARY CELLS

The specific gravity of the solution in a storage battery is an important factor in determining its condition. By the specific gravity of a solution is meant its weight, compared with an equal volume of water. Sulphuric acid is heavier than water, so that if sulphuric acid and water are mixed the resulting solution will be heavier than water alone. If a pint of water weighs a pound, a pint of the mixture might weigh 1.2 pounds. The specific gravity of water could then be stated as 1, and the specific gravity of the solution as 1.2. In order to more readily express fractional values, it is customary to call the specific gravity of water 1,000, in which case the specific gravity of the mixture above referred to would be 1,200. This simply means that the solution is 20% heavier than water alone.

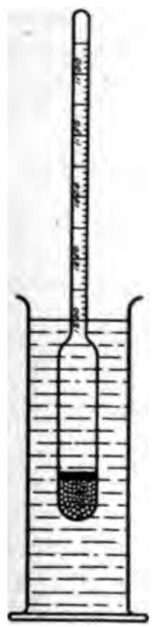


Fig. 70.

The specific gravity of a solution is measured by a hydrometer. This is a glass tube weighted at one end, Fig. 69. The solution to be tested is placed in a tall, slender glass vessel and the hydrometer immersed therein, Fig. 70. It sinks to a certain depth, depending upon the density of the solution. The lighter the solution, the deeper will the hydrometer sink. A scale is provided on the side of the tube so that the specific gravity may be read directly.

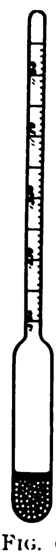


Fig. 69. Hydrometer.

A specific gravity of about 1,200 is a suitable density for the mixture of sulphuric acid and water to be placed in a newly assembled storage battery. In such a solution, about 20% of the electrolyte by weight is chemically pure sulphuric acid.

Figures 71 to 76 illustrate the various chemical actions which take place, during charge and discharge of a secondary cell, as well as the intermediate actions which occur if the cell is allowed

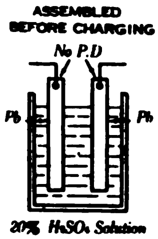


FIG. 71

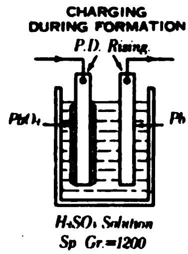


FIG. 72

to rest. Figure 71 represents the plates of a Planté cell assembled in the solution referred to, ready for charge. There is no difference of potential between these plates and the acid tends to attack both equally.

In Fig. 72, as a charging current is applied from left to right, oxygen is developed at the plate where the current enters, which combines with the lead to form peroxide. The hydrogen is evolved at the negative plate in a gaseous form and does not attack it. As the charge progresses, the potential difference rises until finally a maximum of 2.5 to 2.7 volts may be obtained. This drops to slightly more than two volts, immediately upon the cessation of the charging current.

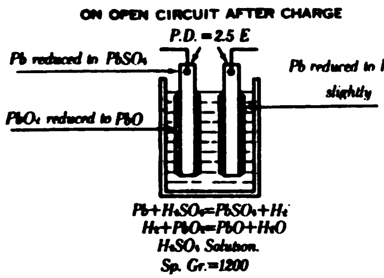


FIG. 73

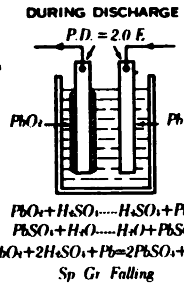


FIG. 74

If now the cell is allowed to rest on open circuit after charging, the conditions illustrated in Fig. 73 now take place. Local action ensues between the peroxide of lead and the plain lead under-

neath it. This causes the peroxide to be reduced to monoxide of lead, and the plain lead to be reduced to lead sulphate, while the sulphuric acid is changed to water. Sulphating also ensues at the surface of the negative plate to some extent. It will thus be seen that the energy which was stored in the form of peroxide of lead is gradually dissipated even though no current is drawn from the cell.

If the preceding action had not occurred, but the cell had been immediately placed on closed circuit after being charged, the action illustrated in Fig. 74 would occur. Lead being positive to its oxides, a current now starts from the plain lead plate on the right, as from the zinc of a primary battery, and flows to the relatively negative peroxide coated plate on the left, as to the carbon in a primary battery. The interchange of atoms now results in the reorganization of the molecules as shown under this figure, a plain lead molecule, a peroxide of lead molecule, and two molecules of sulphuric acid being converted into two molecules of lead sulphate and two molecules of water. As the surface of both plates gradually become coated with lead sulphate, the difference of potential gradually falls. It is not wise to allow the e.m.f. to fall below 1.8 volts, as by that time the amount of lead sulphate formed on the plates coats them to such an extent as to interfere with the passage of the subsequent charging current. It must be borne in mind that lead sulphate is a poor conductor and there must always be enough peroxide left on the positive plate and plain lead molecules on the negative plate to carry the current in and out through the surrounding poor conducting sulphate. This explains the importance of not discharging the cell below 1.8 volts.

Should the cell be allowed to rest on open circuit after being discharged, the conditions represented in Fig. 75 set in. The most injurious sulphating will now occur. During the previous discharge of the cell, monoxide of lead formed to some extent. This monoxide now combines with the lead sulphate to form an exceedingly hard, flint-like, insoluble, non-conducting coating Pb_2SO_5. It is difficult to dissolve Pb_2SO_5 by means of a charging current. The plates may be removed and the hard sulphate scraped off with a tool, but much of the active material is carried with it. In fact, the formation of a large amount of Pb_2SO_5 is generally admitted to be the ruination of any

lead cell. It is, therefore, obvious that a cell should never be allowed to rest on open circuit after discharge. If the solution in a sulphated battery is replaced with water and the battery

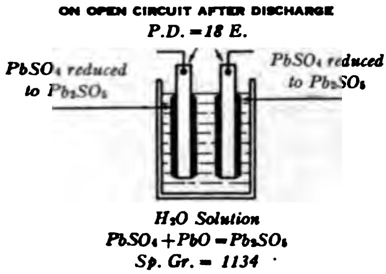


FIG. 75

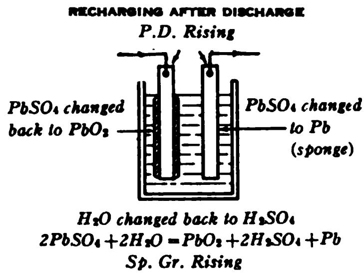


FIG. 76

charged at a low ampere rate for a long time and then refilled with electrolyte of the proper density, and the cell is again charged, the plates will often resume their original condition.

Should the cell be placed on charge immediately after discharge, the conditions illustrated in Fig. 76 will occur. The lead sulphate on the positive plate is changed back into peroxide of lead, and the lead sulphate on the negative plate is changed back into plain sponge lead, while the solution is changed from a watery condition to one containing more sulphuric acid. The specific gravity, therefore, rises during charge, as does the potential difference, while the specific gravity and potential difference both fall during discharge.

The density of the electrolyte in stationary batteries should not exceed 1,200 when fully charged. In order that there shall be enough sulphuric acid to supply the requirements for the formation of lead sulphate on discharge, and of sponge lead and peroxide on charge, it is necessary that there shall be ten pounds or more of electrolyte for every 100 ampere hours capacity in the cell.

Vehicle batteries are constructed to require less solution than stationary batteries in order that they may be lighter and more compact. They require but four pounds of electrolyte for every 100 ampere-hours capacity, but the specific gravity must be somewhat higher; that is, about 1,265.

One of the best indications of the condition of charge in a battery is the specific gravity of the electrolyte. A stationary

battery is discharged to the lowest point considered safe when its specific gravity falls to 1,134. A vehicle battery should not be discharged to a point where the specific gravity is less than 1,137.

The precise condition of the discharge can be easily determined by reading the specific gravity in a pilot cell. Thus, suppose that the specific gravity of a certain cell when charged is 1,285 and when discharged is 1,150. The difference between these values is 135 degrees on the hydrometer scale. If, at a certain time, the hydrometer reading showed 1,217, which is 1,150 + ½ of 135, which is the difference between charge and discharge, it will be evident that the battery is just one-half discharged. In other words, between the divisions 1,150 and 1,285 on the hydrometer scale, the ampere-hour capacity of the battery could be laid off, Fig. 77. Dividing this space into four parts, the scale could be marked ¼, ½, ¾, discharged, etc. This gives an accurate indication of the amount of energy yet available.

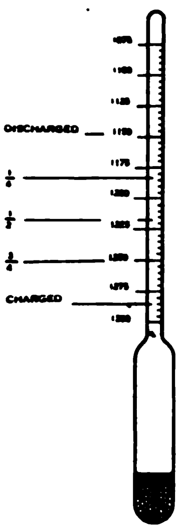


Fig. 77.

As the temperature of the electrolyte increases the specific gravity falls for a given condition of charge. This should be taken into account at all times especially with stationary batteries.

The electrolyte should always be made of chemically pure acid and distilled water. Rain water will answer, but ordinary city hydrant water generally contains enough impurities to ruin any battery. As the heavier solution sinks to the bottom, the current concentrates there and the plates decay more rapidly at the bottom than at the top.

Too much attention cannot be given to securing the proper density of the electrolyte. If too high, the excess of sulphuric acid facilitates sulphating and the plates deteriorate rapidly. On the other hand, if it is too low the lack of a sufficient amount of sulphuric acid prevents the formation of a sufficient amount of lead sulphate and the plates disintegrate. Lead sulphate acts as a binding material to hold the peroxide together. The peroxide has no cohesive properties of itself. A weak solution with

the consequent lack of lead sulphate results in allowing the peroxide to powder off and deposit as a red sediment in the bottom of the cell.

The e.m.f. also varies slightly with the density of the electrolyte. That is, the higher the specific gravity, the higher the voltage of the cell.

Dilute acid is a good conductor. Pure water or pure acid is a poor conductor. It must be evident then that a certain proportion of acid and water will have a maximum conductivity. This is true in regard to the electrolyte of a secondary battery. It has its minimum resistance when the specific gravity is 1,260. The resistance rises if the specific gravity is either raised or lowered.

SECTION III CHAPTER VI

CURRENT ELECTRICITY

CHEMICAL ACTIONS IN SECONDARY CELLS

1. Explain what is meant by the "specific gravity" of a liquid.
2. What is a hydrometer? How is it used?
3. What is a suitable specific gravity for a newly assembled uncharged secondary cell? What percentage of sulphuric acid is required to produce this specific gravity?
4. What are the plates, what is the potential difference between them, what is the solution, and the general condition in a Planté cell assembled for the first time before charging?
5. Explain in detail the chemical actions which occur when a Planté type of cell is charged for the first time.
6. Explain in detail the chemical reactions that take place if a Planté cell is left on open circuit after its initial charge.
7. Explain in detail the chemical actions that take place in a Planté cell during discharge if it has been allowed to rest after its initial charge.
8. Explain in detail the chemical actions that take place in a Planté cell if it is allowed to rest on open circuit after discharge.
9. Explain in detail the chemical actions that take place in a Planté cell if it is recharged immediately after discharge.
10. What is a suitable specific gravity for stationary, for vehicle and for starting batteries both when charged and when discharged?
11. When is the resistance of a solution of sulphuric acid and water the least?
12. If the specific gravity of a secondary cell is 1,285 when fully charged, how much of the initial charge remains available if the specific gravity has fallen during discharge to 1,251?

SECTION III CHAPTER VII

CURRENT ELECTRICITY

SECONDARY CELLS; TYPES

In 1881 Camille Faure made a radical improvement in the construction of storage batteries. A long time was required to form the Planté plate and it was very expensive as well as heavy. Faure mixed a paste of red lead with a solution of equal parts of sulphuric acid and water. This paste was smeared upon a lead plate or pressed into a light cast lead grid. The sulphuric acid attacked the red lead and converted it into a paste of lead sulphate which upon charge was converted into peroxide of lead. A similar paste was made by mixing sulphuric acid and water with litharge or yellow lead. This paste was pressed into a lead grid which upon charge was converted into plain sponge lead. The plate containing the lead sulphate paste constituted the positive plate, while the one containing the paste of litharge constituted the negative plate. Furthermore, the paste was quite porous which made it possible to convert the greater portion of the entire mass into active material. This gave a relatively light cell and one which was much less expensive to form than the Planté.

The Faure type of cell would have come into universal use had it not been for certain defects which developed. In the first place, the Faure paste adheres very feebly to the grid, while the peroxide developed on a Planté plate adheres much more tenaciously. In the next place, the active material expands and stretches the surrounding lead grid. Lead being a very ductile but inelastic material, the grid does not subsequently contract on discharge, but the paste does contract. This causes the active material to become loose in the surrounding grid and after repeated expansions and contractions the blocks of active material eventually crumble up and disintegrate. Various plans have been devised to prevent the active material from becoming loose. Dove-tailed recesses have been formed to hold the pellets of active material in place. The grid has been alloyed with antimony to strengthen it. But in spite of all precautions, the plates finally disintegrate.

Chloride Cell

One of the largest and best known types of Planté cell is the **Chloride,** manufactured by the Electric Storage Battery Company. The positive plate consists of a strong grid of lead and antimony in which pellets of active material are placed, as shown in Fig. 78. A narrow gimped lead ribbon is rolled up into a close spiral and forced as a plug into the hole. Upon subsequent forming the acid circulating through the convolutions of the ribbon converts practically the entire plug into peroxide of lead. In an older form a mixture of lead chloride and zinc chloride was used to form the pellet. The zinc chloride was subsequently dissolved out and the lead chloride converted into metallic lead. This metallic lead base was then converted into peroxide by charging.

FIG. 78.

Gould Cell

A well known form of Planté cell is the **Gould,** manufactured by the Gould Storage Battery Company. A plate or blank of lead is placed in a machine which contains a number of small circular knives which are rotated. The blank is passed back and forth under these revolving knives, which cut down into the lead plate and likewise spin the lead in thin leaves up between the knives. This causes the plate to be covered with a large number of thin leaves projecting outward and causes the actual contact surface of the plate with the acid to be increased between ten and twenty times over its mere superficial area. It is possible to get between two hundred and four hundred square inches of contact surface with the acid per pound of lead plate, and two hundred fifty square inches of contact surface is allowed per ampere of current. Chemically pure lead is used and no lead antimony alloy. This plate is subsequently pickled and then subjected to a charging current which converts the entire

surface into peroxide of lead. The peroxide fills the entire space between two adjacent leaves of lead which acts as a thin web or background to support the active material. It constitutes one of the most substantial and durable forms of Planté cell.

FIG. 79.—Complete suspended type of Gould cell employed for stationary purposes.

Another form of Gould cell of the Faure type is also widely used. This employs a pasted plate construction, illustrated in Fig. 79. The assembly of positive plates is shown in Fig. 80*A*

and the negative plates in Fig. 80*B*. The construction is very substantial and the output high in proportion to its weight.

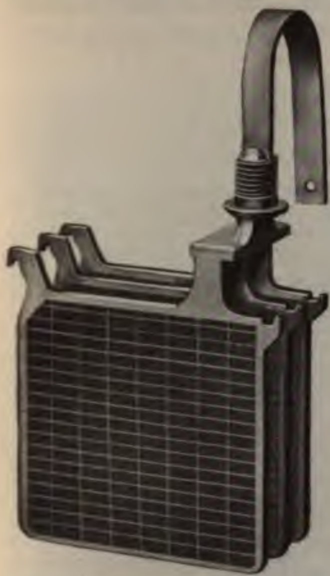


FIG 80*A*.—Positive group of Gould cell.

FIG. 80*B*.—Negative group Gould cell.

Exide Cell

Fig. 83 represents the **Exide** cell. This is a pasted plate of the Fauré pattern, manufactured by the Electric Storage Battery Company for work where a light cell of large capacity is required.

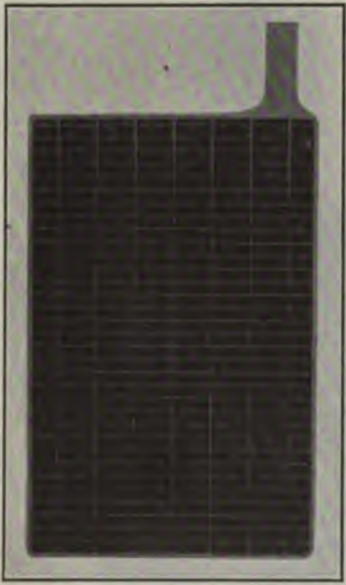


Fig. 81.—Pasted positive plate *MV* Exide type, built by the Electric Storage Battery Company.

Fig. 82.—Pasted "Ironclad" Exide negative plate manufactured by the Electric Storage Battery Company.

A very light lead antimony grid with a paste of lead sulphate pressed into the grid under hydraulic pressure upon charge becomes the positive, while the negative contains a paste of litharge. The pasted grid-type of cell is widely used, and is manufactured by a number of different concerns.

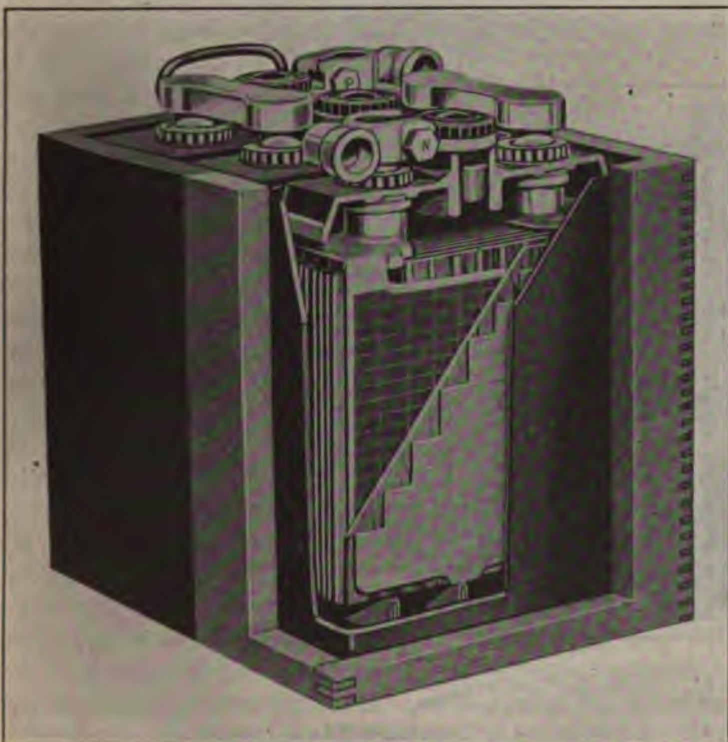


FIG. 83.—View showing construction of portable Exide battery for automobile starting, lighting and ignition work manufactured by the Electric Storage Battery Co.

Iron-Clad Exide Cell

The Electric Storage Battery Company also manufactures what is called the **Iron-clad Exide**. Fig. 84 illustrates the Iron-clad positive plate. There is no iron in the cell, however, the term being simply suggestive of the strong manner in which the active material is held in place. The positive plates are arranged as follows: A number of lead wire rods about $^1/_8$" diameter stand centrally in long, slender, hard rubber tubes about $^5/_{16}$" diameter. The intervening space is packed solid with a paste of lead sulphate which is subsequently converted into peroxide when charged. The sides of the hard rubber containing tubes are slotted horizontally with a large number of very fine slots designed to permit the free circulation of the electrolyte and enabling the active material to be attacked, but at the same time these slots are too fine to allow the active material to ooze out and deposit in the bottom of the cell. The elasticity of the hard rubber allows for the expansion of the active material to a limited extent, without breaking. A row of these tubes of active material is mounted in a lead frame.

FIG. 84.—"Iron-clad" positive plate of the Electric Storage Battery Co.

The hard rubber tubes have a projecting rib on the sides next to the negative plates, which obviates the necessity for separate spacing insulators. The negative plates in the Iron-clad cell are practically the same as those used in the ordinary Exide. The Electric Storage Battery Company claims that for some vehicle work the Iron-clad Exide will last three times as long as the original Exide.

Edison Bimetallic Cell

The Edison Storage Battery Company manufactures a bimetallic accumulator, which is the invention of Thomas Edison.

It consists of a nickel-plated steel can which contains two sets of nickel-plated steel grids which in turn contain receptacles for the active material, Fig. 85. The positive plate contains a series of perforated steel tubes, Fig. 86, in which is packed a

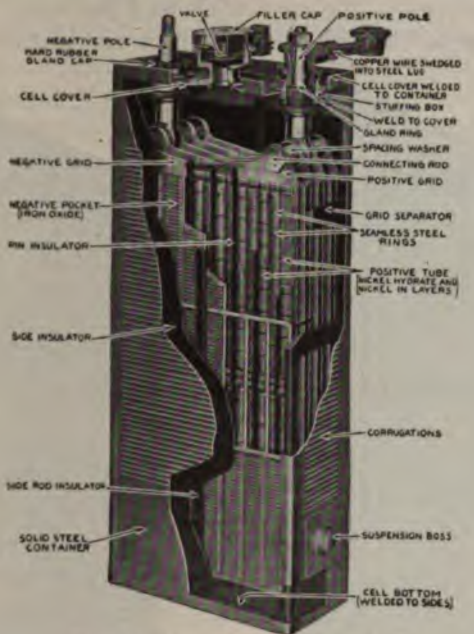


Fig. 85.—Complete Edison cell.

compound of nickel interspersed with leaves of pure nickel foil. This foil is to conduct current through the poor conducting nickel compound. The negative plates, Fig. 87, contain small boxes, which are also perforated and contain a mixture of 50% graphite and 50% finely divided compound of iron. Graphite, like the nickel foil in the positive plate, plays no part in the chemical action but simply gives conductivity to the mixture. This box and also the tubes are riveted in place in the steel grids. Although the active material expands and contracts, as in a lead cell, the expansion and contraction is well within the elastic limit of the steel grid, so that this material never becomes loose in its receptacles. The plates are insulated from each other and from the surrounding receptacle by the minimum space necessary for clearance.

The solution is a 21% mixture of potassium hydroxide. The solution is required simply to form a conducting path between the plates, hence a very small amount is necessary as it plays no part in the chemical actions. A definite weight of solution is not required, as is the case with lead batteries. A charging current is sent through the cell from the nickel to the iron.

FIG. 86.—Positive element.

FIG. 87.—Negative element.

This deoxidizes the iron compound and oxygen is conveyed through the solution against the current to the peroxide plate, where it attacks the nickel compound and forms a super-oxide of nickel.

When charged the cell has a maximum e.m.f. of 1.33 volts which falls to 1.2 when working. On discharge, current flows from the iron plate to the nickel. The nickel is gradually reduced to a lower state of oxidization while the iron plate becomes oxidized.

The type A-4 battery has four positive plates and the charging rate is 7.5 amperes per positive plate. Thus 30 amperes are required to charge this cell and this is also the normal discharge rate. The charge should be continued for seven hours which

gives the cell 210 ampere-hours. On discharge thirty amperes may be drawn for about five hours or 150 ampere-hours capacity. The ratio of the ampere hours delivered to the ampere hours absorbed is therefore 70%, which is approximately the efficiency of the battery.

An e.m.f. of 1.85 volts per cell is necessary to charge the Edison Battery. Thus, sixty cells would require 111 volts, although an ordinary 110-volt circuit will do.

The battery may be discharged without injury, until its e.m.f. drops to zero. The plates do not deteriorate, there is no sediment to deposit in the bottom of the cell, as is evidenced by the fact that the tops on the jars are welded and the plates cannot be removed. Charging or discharging at too high a rate or even reversing the direction of current in a cell produces no injurious results. In fact, it is claimed that the cell is fool-proof and requires no expert attention of any character. It has an output of fourteen watt-hours per pound as compared with seven watt-hours per pound for the lead cell.

Another advantage of this battery is that its capacity increases after it is put into service, up to a maximum of 30%. This is because repeated charging and discharging renders the active material of the positive plate more porous. This battery has its highest capacity when charged at the normal rate for ten hours instead of seven hours, although the efficiency is somewhat sacrificed. It is quite expensive, costing about three times as much as a lead cell of the same watt-hour capacity. One criticism that can be made of the battery is that high efficiency as relates to the charge which it contains, can only be had if it is operated at a temperature between 70 and 100 degrees Fahrenheit. If the battery gets very cold or very hot, there is a decided loss of charge. It is also claimed that an attempt to draw an excessive current is accompanied by such a fall in potential as to make it impossible to draw more than a limited amount of energy. Hence it has not come into use for cranking automobiles.

It is wise to empty out the solution and renew it about once in ten months. The specific gravity of the new solution should be 1,200 degrees and it should never be allowed to fall below 1,160.

SECTON III CHAPTER VII

CURRENT ELECTRICITY

SECONDARY CELLS; TYPES

1. What was the improvement in secondary cells invented by Faure? Explain the preparation of the material for the positive and negative plates.

2. Explain the construction of the chloride secondary cell. How are the positive and negative plates prepared?

3. Explain the construction of the Gould secondary cell. How are the plates prepared?

4. Explain the construction of the Exide secondary cell. How are the plates prepared?

5. Explain the construction of the "Iron-clad" Exide secondary cell. What are its advantages and disadvantages over the other type of Exide?

6. Explain the construction of the Edison secondary cell. Of what does the active material consist? What is the solution employed? What is the initial and working e.m.f.? What are its advantages and disadvantages over the lead cell?

SECTION III. CHAPTER VIII

CURRENT ELECTRICITY

CARE OF SECONDARY BATTERIES

If a battery is received in a dry condition it should be put in commission in the following way:

First, the plates with separators between them should be mounted in the retaining jar. The specific gravity of the electrolyte to be used will depend upon the condition of the plates. If the plates are new, the cell should be filled with electrolyte of a specific gravity of about 1,350. This varies with different manufacturers.

If the plates are from a battery which has been used before and new separators are used, the electrolyte should be 50 points higher than the old electrolyte.

If old plates and old separators are used the electrolyte should have the same specific gravity as that which was originally taken from the cell before it was disassembled.

The introduction of the electrolyte will cause the temperature to rise. The cell should be allowed to remain idle for about ten hours in order to cool off. It should then be placed on charge at about two-thirds the normal rate and the charge should be continued incessantly until the specific gravity and voltage show no further rise over a period of ten hours and all the cells are gassing freely. This will require at least sixty hours with new plates while if old plates are used which have either sulphated or dried out, the duration of the charge may have to be increased to ninety or one hundred hours before the specific gravity and voltage cease to rise.

To determine when a battery is fully charged: First, the specific gravity should be high; from 1,200 to 1,300, according to type. Second, the e.m.f. should be high, that is from 2.5 to 2.7 volts per cell while charging at the normal rate, according to the concentration of the electrolyte. Third, the cells should all boil or gas freely. This does not mean that the cells will rise to a boiling temperature but that they have the appearance of boiling due to the free evolution of oxygen and hydrogen gases which can no longer combine with the plates when they are fully charged.

A summary of the rules for the proper care of a lead type storage battery follows:

1. A battery may be charged or discharged at any rate which does not cause the temperature to rise above 110 degrees Fahrenheit or does not produce excessive gassing.
2. A battery must never be left idle in an uncharged condition.
3. The specific gravity must be kept within the range of 1,134 minimum when discharged, and 1,285 maximum when charged. The actual range depends upon the type of battery.
4. The plates must always be kept well covered with electrolyte.

The ampere-hours which may be taken out of a cell depends upon the rate at which the current is drawn. The higher the rate of discharge the less the total ampere-hours delivered or work done. Stationary batteries are rated on an eight-hour basis, that is, a cell of this type rated at 100 ampere-hours would deliver current at the rate of 12½ amperes for eight hours. Vehicle batteries are sometimes rated on a four-hour basis. A vehicle battery rated at 100 ampere-hours would deliver 25 amperes for four hours. Batteries for electric cranking of automobiles have two ratings, one at a low rate for lighting and one at a higher rate for cranking. Thus, in the following table an Exide Battery has a rating of 105 amperes at the 3 ampere rate of discharge but as the amount of current drawn increases the actual ampere-hours available decreases. Thus it will be seen that for a delivery of 114 amperes, the total output would amount to only 38 ampere-hours, for the battery could not deliver this current for more than twenty minutes before the voltage drop would be excessive.

Exide Cranking Battery

Type XC-15 and similar

Amperes.	Hours.	Ampere-hours.
3	35	105
5	20	100
7.5	12.4	93
10	8.8	88
114	20 mins.	38

The reduction in available capacity at higher rates of discharge is due to the depletion of the acid in the pores of the plates. The rate of this depletion is the difference between the rate of absorption of the acid that is in the pores of the plates, by the plates, and the rate at which this acid is renewed by diffusion with the other acid in the cell.

While modern batteries are able to deliver practically any current that may be required of them, it is a safe rule not to discharge a battery at a rate in amperes which is greater than the ampere-hour rating of the battery. Thus, a cell rated at 100 ampere-hours should not be discharged at a rate in excess of 100 amperes. This rule, however, is violated in the matter of cranking batteries for automobiles, where at the moment of starting the current delivery is often greatly in excess of the above limit. This rate, however, lasts for a short time only and when the engine turns over the rate falls to within the prescribed amount.

Vehicle and cranking batteries generally have the positive and negative plates separated by chemically treated wooden separators about $\frac{1}{16}$th of an inch thick. To prevent them from deteriorating before they are put in the battery, they are kept moistened in a very weak solution of sulphuric acid and water. If they are allowed to dry they are worthless, hence they must be always kept moist. These separators last a year or more. When a battery is taken down to wash out the accumulated sediment in the bottom of the jar due to the shedding of the active material, the separators should be replaced with new ones. To avoid the necessity for frequent renewals one company has produced what they term a **threaded rubber insulation,** which is a sheet of hard rubber perforated with about 6.500 fine holes to the square inch through each of which is threaded a minute wick which allows the electrolyte to make moist contact and the chemical actions to take place but which absolutely prevents the active material of one plate from touching the adjacent plates of opposite polarity. Thus while it prevents internal short-circuiting it does not increase the internal resistance appreciably. These separators have been found to be in good condition after three years of service.

All batteries that are not charged every day should be given a thorough boiling out at intervals of two weeks. If a battery

is to be set away idle for a period of two or three months, it should be given a thorough boiling out at intervals of two or three weeks. This consists in charging the battery at from two-thirds to the full normal rate in amperes, until specific gravity and voltage show no increase over a period of from five to ten hours.

There is always a certain amount of evaporation of the solution. This should be replaced with distilled water. If, however, the solution is sprayed out or leaks out through a broken jar, fresh electrolyte of the proper density should be added.

It is very important that the specific gravity should be maintained sufficiently high. If the solution becomes weak there will be a lack of lead sulphate. Now, lead sulphate acts as a binder to hold the active material together, and in the absence of sufficient sulphate the active material will fall off and accumulate as a brown powder in the bottom of the cell.

Acid of too high specific gravity is also objectionable, as it causes injurious sulphating through local action.

The approximate range through which the specific gravity should vary between charge and discharge, and the proportion of electrolyte to the ampere-hour capacity which is required to effect the necessary chemical combinations in the cell, for batteries designed for different classes of work, is shown in the following table:

100 ampere hour battery.	Specific gravity.		Weight of electrolyte.
	Charged.	Discharged.	
Stationary Battery	1200	1134	10 pounds
Vehicle Battery	1265	1137	4 pounds
Cranking Battery	1285	1150	2.8 pounds

Batteries may be charged from any source of direct current or from alternating current through rectifiers. It is necessary to have at least three volts available for each cell to be charged in series. Constant potential sources of 110 volts are most commonly used for battery charging.

Planté originated the plan of charging a battery in two sections of equal voltage which were connected in parallel. These

could then be rearranged in series for discharge. A resistor should be inserted in series between the source and the battery under charge which will limit the current to the proper value.

The life of the plates in a storage battery depends upon the treatment they receive—that is, upon the rapidity of the charge and discharge and not upon the work which the battery is called upon to do, or upon the ampere-hours delivered.

Long-continued charging does not necessarily injure a cell provided the charging is not at too high a rate.

One of the causes of disintegration of the plates is technically known as **buckling.** This is due to unequal distribution of the current over the surface of the plate.

If two adjacent plates approach each other more closely at one point than elsewhere the current will concentrate at this point. This will cause more expansion of the active material at this point than elsewhere. The plate will become convex and these points will approach still more closely, which causes a still greater concentration of the current until the plate warps so badly as to break the grid and loosen the active material, which then falls out. By using substantial insulators between plates and by very careful spacing, buckling may to some degree be prevented.

Because of the concentration of the electrolyte in the lower part of the cell, the current is denser in this portion than in the upper part. This causes the plates to disintegrate more rapidly in the lower half than in the upper part.

The efficiency of a lead storage battery in good condition is approximately 75%. After it has been in service, however, for a few months, it is rare that the actual efficiency of energy delivered compared with that required to charge, is more than 50% or 60%.

The positive side of the electrical source must be connected to the peroxide of lead plate in a battery to charge. A simple test to determine the polarity of a source is the following: Moisten a piece of white blotting paper with a few drops of 10% iodide of potassium solution. Attach the two wires leading to the electrical source to the moistened spot about an inch apart. The blotting paper around the positive wire will turn a dark chocolate color. This wire is to be connected to the dark brown peroxide plate of the battery to be charged.

If a battery is to be left idle for more than six weeks, it should be dismantled. To do this, proceed as follows:

1. Charge the battery fully; that is, boil it out thoroughly.
2. Draw off the electrolyte. If this is in good condition it may subsequently be used again.
3. Fill the jars with water and allow the plates to soak therein for five hours.
4. Remove the plates; wash them in clean water, dry and pack away.

The life of the plates of a storage battery is quite uncertain. In stationary service, the positive plates will last upwards of ten years and the negative plates upwards of 15 years. In vehicle work, the positive plates generally last 18 months or less, while the negative plates last three years or less.

Cranking batteries for automobiles last from one to two years. In every case the ultimate life of a battery depends upon the treatment it receives. If the specific gravity is kept within the required range, never being allowed to get too high or too low; if the electrolyte is always kept above the plates; and if the charging and discharging rates are kept within the specified normal ampere rating, the life of all batteries will be very materially prolonged.

It is important that the solution be kept one-half inch higher than the tops of the plates at all times.

When an old battery, which has been dismantled, is put into service again, the jars should be immediately filled with electrolyte so that the wooden separators will not dry out. If the old electrolyte is used again, enough new, with a specific gravity of 1.200 to 1.280, depending on the type, should be added to replace the loss. As soon as the cells have been filled with electrolyte, and they have had sufficient time to cool off, the battery should receive a long and continuous charge, precisely similar to the initial charge given to a new battery.

Storage battery solutions of different densities freeze at the following temperatures:

Sp. gr.	Condition of charge.	Temp. Fahrenheit.
1120	Discharged	20 above zero.
1160	$\frac{3}{4}$ths	zero.
1210	$\frac{1}{2}$	20 below.
1260	$\frac{1}{4}$	60 below.

From the foregoing it will be observed that whether or not an automobile cranking battery will freeze, if allowed to stand in the open in cold weather depends very materially upon the condition of charge. If well charged, there is little danger of freezing, but if a battery is run down by long-continued cranking on a cold day, and the car is then allowed to stand, the battery will in all probability freeze, burst the containing jars and ruin the plates.

SECTION III CHAPTER VIII

CURRENT ELECTRICITY

CARE OF SECONDARY BATTERIES

1. How should a battery be treated when assembled for charging the first time?
2. What various things influence the specific gravity of the solution to be placed in the battery when first assembled?
3. In what three ways can you determine when a secondary battery is fully charged? Which is the most accurate indication?
4. What determines the maximum rate at which a battery may be charged or discharged?
5. If a battery is to be left idle, should it be left in a charged or discharged condition? Why?
6. What are the maximum and minimum values of specific gravity for charged and discharged cells?
7. At what height should the electrolyte be maintained in a cell?
8. In what units is the capacity of a secondary battery represented?
9. What governs the actual energy which may be drawn from a secondary battery?
10. Under what conditions would the maximum ampere-hour capacity of a battery be realized?
11. Upon what basis as to time are stationary batteries, vehicle and automobile starting batteries rated?
12. With the exception of starting batteries, what is the maximum rate at which it is considered wise to discharge a battery?
13. What is the nature of the separator employed between plates of opposite polarity in automobile starting batteries? Why is this used?
14. Explain the nature and advantages claimed for the threaded-rubber separator employed by the Willard Company.
15. If a battery is to remain idle for a few months and is not to be dismantled, how should it be treated?
16. As the solution in a battery is constantly depleted by evaporation, how should it be replenished?
17. If loss of electrolyte occurs through a cracked jar, how should it be replenished?
18. What is the danger involved in allowing the specific gravity of electrolyte to become either too high or too low?

19. What are the upper and lower limits through which the specific gravity should range in an automobile starting battery?

20. What kind of current is necessary for charging a battery? Sketch suitable connections, including necessary apparatus, for charging a 6-volt battery from a 110-volt generator.

21. What governs the ultimate life of a battery? What precautions should be taken to insure a maximum life?

22. What is the efficiency of a lead battery? What relation has the time interval between charging and discharging to do with the efficiency? What has the age of a battery to do with its efficiency?

23. How may the polarity of a direct current source for battery charging be ascertained? To which plate in a lead battery must the positive side of the source be connected?

24. If a battery is to be taken down and put away for a long time, what is the procedure?

25. Under what conditions will a storage battery freeze? What precaution should be taken to prevent freezing?

SECTION III CHAPTER IX

CURRENT ELECTRICITY

ELECTRO-METALLURGY

There are three applications of electro-chemistry to metallurgy:

1. The reduction of metals from solutions of their own ores.
2. Electro-typing.
3. Electro-plating.

Copper Refining

Almost all of the copper produced in this country is refined in an electrolytic bath. Crude copper of from 96 to 98% purity is obtained from the smelting furnaces. It is made into plates about 3′ × 2′ × 1″ thick. These plates weigh approximately 250 pounds and are hung in large containing cells in a solution of from 12 to 20% copper sulphate which contains from 4% to 10% sulphuric acid. These slabs of impure copper constitute the anodes and are separated 1″ from a chemically pure copper sheet about 1/20″ thick, which constitutes the cathode. A current is sent from the impure anode to the pure copper cathode with an e.m.f. of between 0.2 and 0.4 volts. The reason that so small an e.m.f. is required is because the energy given up at the anode almost exactly balances the energy required to deposit copper at the cathode; therefore it is only necessary to supply sufficient e.m.f. to overcome the internal resistance of the cell. A current density of from 10 to 15 amperes per square foot of cathode surface is employed. Generators delivering 125 volts are used and a considerable number of cells are connected in series. It takes from 400 to 450 ampere-hours to refine one pound of copper. All impurities are left in the solution. Among these impurities is a considerable amount of gold and silver, which can be recovered from the solution afterward. It is not unusual to recover fifty dollars worth of gold and silver from every ton of copper refined. From eight to nine pounds of copper are refined for every k.w. hour at a cost of about 0.7 cent per pound.

Production of Aluminum

Aluminum is refined by the Hall process at the plant of the Aluminum Company of America at Niagara Falls and elsewhere.

The Hall process dates from 1886 and consists in electrolyzing alumina which is dissolved in a bath of fused cryolite. The process is as follows: Large iron retorts, *F*, Fig. 88, lined with graphite, *E*, are electrically connected in series across rotary

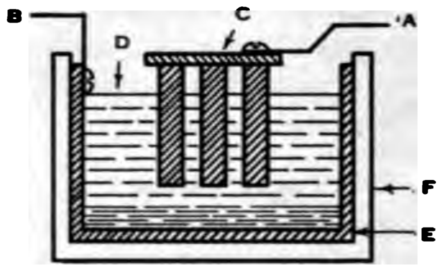


FIG. 88.—Electrolytic bath for producing aluminum.

converters or direct-current generators, which furnish the required current. In the center of each retort there is suspended a bank of some forty carbon rods, *C*, 3″ in diameter and 18″ long. These constitute the anodes of the cell and are gradually consumed.

Alumina (Al_2O_3), which is an oxide of aluminum, is obtained from the mineral bauxite which is found in abundance in Georgia, Alabama and elsewhere. Bauxite is treated to drive off the impurities by mixing it with a little carbon and heating in an electrical furnace. The impurities are thus reduced and collect in the bottom of the mass. This leaves the alumina nearly pure, which may be tapped off while fused, or easily broken up and removed when cool. It requires two pounds of alumina to produce one pound of aluminum.

Cryolite is a natural double fluoride of aluminum and sodium found in Greenland. This is melted in the carbon lined retorts above referred to and forms the conducting electrolyte, *D*. An e.m.f. of between 5 and 6 volts is applied to each cell. The energy required for each retort is about 65 h.p.

Alumina, which is the basis of the product aluminum, is fed into the molten cryolite bath. About three volts are required to decompose the alumina. The remaining three volts are utilized in generating the heat necessary to maintain the bath at the required temperature, 850 to 900 degrees Centigrade. As the current passes from *A* to *B* the alumina is decomposed and

pure aluminum is evolved and deposited on the bottom of the tank, *E*, as a molten metal more than 99% pure.

The oxygen which is evolved at the carbon anodes combines therewith and is given off as carbonic oxide. One pound of carbon anode is consumed for every pound of aluminum produced. When the alumina is exhausted the e.m.f. across the cell rises. This actuates a relay which is shunted across the electrodes and lights a lamp, thus giving a signal which indicates that more alumina should be fed into the retort.

It requires about one electrical h.p. for a 24-hour day to produce one pound of aluminum. Aluminum originally cost about $15 per pound. Due to the cheapness of hydro-electric power at Niagara Falls the cost was reduced in 1915 to about thirty cents a pound.

Electrotypes

In 1836 deLaRue observed that copper deposited in a Daniell cell took the exact impression of the surface of the copper electrode, even reproducing perfectly the most minute scratches. This suggested the possibility of reproducing ornaments, coins, plates, etc., of irregular surface in the electrolytic bath.

The process was developed by Jacobi and Jordan in 1839. A mould is made of wax or plaster and on its surface an impression is made, of the type which has been set for the page of a book, or any other irregular surface, such as a coin or a metal, which it is desired to reproduce. Both before and after taking the impression, the metal must be coated with plumbago, graphite or bronze, which is dusted over the surface with a camel's hair brush. A metallic connection is made to the edge of the coated mould, after which it is hung as the cathode, *C*, in a saturated, slightly acid, copper sulphate solution, with an anode of pure copper, *A*, Fig. 89. Copper is deposited atom by atom in the mould and after a sufficient depth has been deposited to give it a good body, it is removed from the bath, cleaned with acid and backed up by molten lead or some other base metal. This gives a reproduction of the original type, but with a durable copper face. This is called an electrotype. The majority of text-books are printed from electrotypes. While the cost is somewhat greater than when the plates are made of lead, the electrotype is much more durable and many editions of a book can be printed from one set of plates.

Vases, duplicating the most elaborately ornamented bronzes may be reproduced by making separable plaster casts thereof, coating the inner surface with plumbago, filling the mould with copper sulphate solution, and immersing a copper anode therein. Flowers and fruits can be immersed in a thin solution of benzine

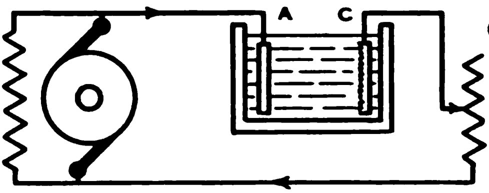


FIG. 89.—Making electrotypes.

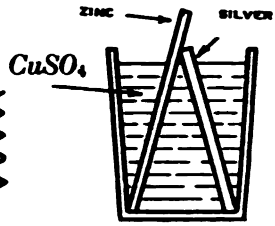


FIG. 90.—Principle of electroplating.

and beeswax, then dusted over with powdered graphite and immersed in the electrolytic bath. A thin film of copper may be deposited over them, which hermetically seals the fower or other article, making it everlasting. The product may be treated with acid to produce various colors which are very pleasing to the eye. Fine lacework may also be reproduced.

Electroplating

In 1801 Wollaston observed that if a plate of zinc and a plate of silver were mounted in a copper sulphate solution and short-circuited, as shown in Fig. 90, the silver would receive a plating of copper. This was due to the deposition of copper atoms on the silver by the current which passed through the solution. The current was due to the difference of potentials between the zinc and the silver. This was both a voltaic and an electroplating cell, in one. In 1805 silver medals were gilded by immersing them in a solution of gold.

In 1840 Messrs. Elkington Brothers introduced commercial electroplating. This consists in depositing a thin skin of metal upon an inferior base. In order that this shall be accomplished successfully, it is of the greatest importance that the metal to be plated shall be chemically clean, or the result will be poor.

To prepare an article of copper or brass for the plating bath it should be immersed in a stripping solution, made of one part nitric acid, one part sulphuric acid and two parts water. This thoroughly cleanses the surface of the article, after which

it should be rinsed in clean water. There are a number of plating solutions for depositing various kinds of metals, but only the most important ones will be mentioned here.

Copper Plating

An excellent copper-plating solution for depositing copper on anything except iron, is made as follows:

A saturated solution of copper sulphate must be made, to which is then added one-fourth its volume of water, containing 10% of sulphuric acid. A saturated solution is one in which all of the copper sulphate crystals have been dissolved that the solution will take up.

Another copper-plating solution for any material, including iron, is known as the cyanide bath. It is made as follows:

5 oz. carbonate of copper.
2 oz. carbonate of potash.
10 oz. cyanide of potassium, C.P.
1 gallon of water.

Silver Plating

A silver-plating bath may be made as follows:

Dissolve four ounces of cyanide of potassium in one gallon of water. Insert a large silver anode, *A*, and a small silver cathode, *C*. Pass a large current through the solution, Fig. 91, until one ounce of silver has been dissolved therein, over and above that which has been plated on the cathode. The solution is then "charged" with silver. Hydro-cyanic acid should be added to neutralize the caustic potash that is formed, and the solution is now suitable for use for deposition of silver. The electrodes referred to are removed, a pure silver anode is introduced and the article to be silver-plated is immersed as a cathode.

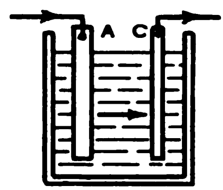


FIG. 91.

Gold Plating

A gold-plating solution may be made as follows: Dissolve four ounces of cyanide of potassium in one gallon of water. Insert a large gold anode and a small gold cathode. Pass a large current through the solution until one ounce of gold has been dissolved therein over and above what has been deposited

on the cathode. This solution is now suitable for use in deposition of gold. The electrodes referred to are removed and a pure gold anode is introduced and the article to be gold-plated is immersed as a cathode. When plating with gold, the solution must be used hot and kept in motion to insure a good, smooth deposit.

Nickel Plating

A nickel-plating solution is made as follows: Dissolve 12 to 14 ounces of double nickel salts in one gallon of water until the specific gravity is between 1.041 and 1.057. These salts are a double sulphate of nickel and ammonium. Nickel-sulphate is a poor conductor, but is necessary for the deposition of nickel. Ammonium sulphate is a good conductor, but would not attack the nickel anode to replenish the solution. Therefore, the double nickel sulphate above mentioned is necessary.

In depositing nickel there should be from 3″ to 6″ between the anode and the cathode. The current should be adjusted to a value which will show gas bubbles adhering to the surface of the work, but the current should not be sufficiently heavy to cause the bubbles to leave the cathode and come to the surface freely.

To insure nickel plating adhering firmly to an iron base, the iron should first be copper plated. This can be accomplished by immersing the iron for a few moments in the cyanide bath, where with a moderate current a "strike" of copper can be obtained in a few moments. Copper adheres well to iron, and nickel to copper, but nickel will not adhere firmly to iron.

There is a tendency for nickel-plated work to deposit dark or even black. The addition of 10% of common salt to the plating solution tends to whiten the deposit and make it tough and firm.

Nine-tenths of the failures to secure good results in electroplating are due to imperfect preparation of the article to be plated. If an article is held under running water, the water will adhere to it in spots if it is not clean, but if it is clean the water will run smoothly over the entire surface. Under all circumstances, and with all metals, a weak current will give a slow, dense and fine-grained hard deposit, while a strong current produces a softer, more open and even crystalline deposit.

The following instructions will indicate the order of procedure in plating with nickel:

1. Buff the article on a fine muslin buffing wheel, using Tripoli

polishing compound until the article has the desired smooth finish.

2. Immerse in a solution composed of 2 ounces of XXX lye in one gallon of water, and boil on stove for 5 minutes. The article must be firmly but lightly attached to wires by which it is to be suspended in the plating solution to avoid the necessity for touching it after it comes out of the lye.

3. Dip the article in a solution composed of ten ounces of cyanide of potassium in one gallon of water for a moment to remove the stains of the lye.

4. Rinse the article in cold, running water, being careful to handle it entirely by the supporting wires. It must not be touched with the hands. If the water runs smoothly over the entire surface, it is chemically clean.

5. Support the article *C* by the attached wires in the nickel-plating bath, Fig. 92. This solution should have its surface cleaned by passing a sheet of tissue paper over it just before the

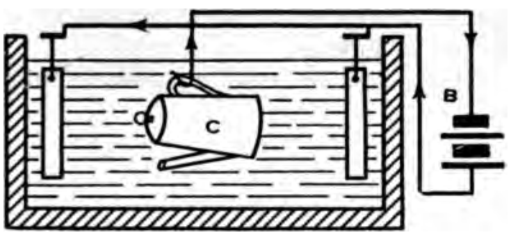


FIG. 92.—Nickel plating bath.

articles are immersed. This will remove the dust accumulation which would otherwise adhere to the article to be plated where it was immersed.

6. Adjust the current from one or two cells of battery *B* to a sufficient strength to show minute gas bubbles adhering to the surface of the article. But the current must not be strong enough to cause the gas to bubble up through the solution. The current strength may be regulated by the number of anodes, their distance from the cathode, and the depth to which they are immersed in the solution.

7. Plate the article for from 20 to 45 minutes, depending upon the thickness of the deposit required.

8. Remove article from bath, rinse in hot water and throw it

into a box of sawdust to dry. (The sawdust should cover the article.)

9. Buff the article on a clean, fine muslin buffing wheel, using Vienna lime, the article being slightly moistened to make it adhere. The desired color and polish can thus be effectively obtained.

The bowls of silver spoons and the interior of silver mugs are gilded by the method illustrated in Fig. 93. The mug is filled with a gold solution to the desired height and then is made the cathode of an electrical circuit, which includes one cell of battery. The mug is placed upon a stove where the solution may be kept hot. The positive terminal of the battery is connected to a fine wire of pure gold which is immersed in the solution and serves as the anode. A strike of gold can be obtained in a few moments.

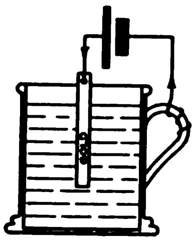


FIG. 93.—Gold plating interior of silver mug.

The following current densities are suitable for articles to be plated in different solutions:

Copper, acid bath, 5 to 10 amperes per square foot of cathode surface.

Copper, cyanide bath, 3 to 5 amperes per square foot of cathode surface.

Nickel, double sulphate, 6 to 8 amperes per square foot of cathode surface.

Gold, chloride bath, 1 to 2 amperes per square foot of cathode surface.

Silver, cyanide solution, 2 to 5 amperes per square foot of cathode surface.

SECTION III CHAPTER IX

CURRENT ELECTRICITY

ELECTRO-METALLURGY

1. What are the three applications of electro-chemistry to metallurgy?
2. Explain the method of refining copper by electrolysis.
3. Explain in detail the refining of aluminum by the Hall process.
4. Explain in detail the production of electrotypes.
5. Explain in detail the process of copper electro-plating with the sulphate bath. Give solution employed, suitable current density and voltage required. When should this bath be employed?
6. Explain in detail the process of preparing articles for electro-plating.
7. Explain briefly the process of nickel-plating. Give solution employed, suitable current density and e.m.f. required.
8. Explain briefly the process of silver-plating. Give solution employed. suitable current density and e.m.f. required.
9. Explain briefly the process of gold-plating. Give solution employed, suitable current density and e.m.f. required, and any other points to be observed.

MAGNETISM

HISTORICAL

Throughout Asia Minor and particularly in Magnesia there is found a hard, black mineral substance known as **magnetite.** The chemical composition of this material is Fe_3O_4. That is, three atoms of iron, chemical symbol Fe, and four atoms of oxygen, chemical symbol O, are combined in each molecule, making an oxide of iron. This substance was known to the ancients and possessed what they thought was a magic property, namely, that of attracting small pieces of iron. They knew nothing more concerning it for centuries.

About the tenth or twelfth century, however, it was found that if fragments of magnetite were suspended by a thread, they would take up a definite direction, pointing north and south. Although this discovery was not known to the civilized world until the tenth or twelfth century, Professor Ewing states that there is a tradition that this property was known to the Chinese between three and four thousand years previously. According to this tradition, Hoang-ti, a Chinese navigator, used a piece of magnetite floated in a vessel of water for the purpose of navigating a fleet of ships when out of sight of land, 2,400 years B.C. As soon as its directive force became known, advantage was taken of the property as an aid to navigation and the material thereafter was commonly known as **lodestone** or **leading stone.** This iron ore is found in all parts of the world. Large quantities are found in New Jersey and Arkansas. It is sometimes referred to as a natural magnet.

If hard pieces of steel or iron are rubbed with a lodestone they acquire the same properties, namely of being able to attract other pieces of iron and of pointing north and south. In 1729 Savery discovered that hard steel retained magnetism much better than soft iron.

Nothing more concerning magnetism was known until the year 1600 when Dr. Gilbert conducted a line of research and published an account of his magnetic discoveries. He found that the attractive force of a magnet appeared to reside in two regions, usually the ends of long magnets, which he designated as **poles.**

The portion of the magnet which lies between the poles is less magnetic. In a uniformly magnetized bar, there is a region exactly midway between the poles where there is no external magnetism at all. This region Dr. Gilbert called the equator. An imaginary line through the bar joining the poles was termed the axis.

Magnetic forces may be observed with a suspended magnetic needle and a bar magnet. The needle is made of steel mounted on a pivot and is magnetized by being rubbed upon a magnet. It will then take a northerly and southerly position when suspended. If a bar magnet is now taken in the hand and one end approached to the two poles of the needle alternately, Fig. 94,

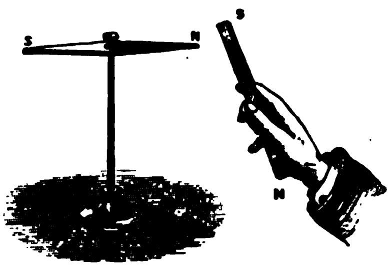


FIG. 94.

it will be observed that one pole of the needle is attracted by the north pole of the magnet while the other is repelled. Now suspend two magnetic needles and ascertain which of their poles tends to point north. Next, approach the north-pointing pole of one needle to the north-pointing pole of the other needle and observe that repulsion ensues and that the north-pointing pole of one will attract the south-pointing pole of the other.

The nature of the magnetism which appears to reside in the polar extremities of a bar or needle seems to be of two opposite kinds, which exert attractions or repulsions upon each other, in very much the same way as the two opposite kinds of electrical charges. One of these magnetic poles tends to move toward the north and the other tends to move toward the south of the earth. It has been proposed to call the two kinds of magnetism north-seeking magnetism and south-seeking magnetism. It is sufficient, however, for our purpose to distinguish between the poles; thus one end is called the **north pole** and the other the **south pole.** As there is some confusion regarding the actual pole which is to

be known as north, it is well to be clear in this matter. If the north-pointing pole of a needle is attracted by magnetism at the north pole of the earth, the law that unlike poles attract shows that these two poles are really magnetically of opposite sign. Which then shall be called north magnetism? If we say that pole which points to the north contains north magnetism we must suppose that the magnetism at the north geographical pole of the earth is really south. The French and the Chinese call the north-pointing pole of a needle a south pole, and the south-pointing pole a north pole. To avoid all confusion, however, **it is customary in this country to call that pole of a magnet which would, if the magnet were suspended, point geographically north, the north pole, and the other the south pole.**

First Law of Magnetism

The foregoing observations may be summed up in the statement that **like magnetic poles repel each other, and unlike magnetic poles attract each other.** This is the first law of magnetism.

Although it is possible to isolate positive and negative electrical charges from each other, it is impossible to obtain a magnet with only one pole. If a steel rod is magnetized by rubbing it with a magnet on one end it will be found to possess a pole at the opposite end also. And if the bar is broken into two or more parts, each part will possess two poles, opposite in sign.

Gilbert made a distinction between magnets and magnetic substances. A magnet exhibits attractions only at its poles but a piece of iron is attracted by either pole of a magnet. It has no clearly defined fixed poles and no magnetic equator. **A magnet, then, is a magnetic substance in which polarity has been developed.**

Iron and steel are the most highly magnetic substances known. Nickel is also quite magnetic though not nearly so much so as iron. With these exceptions there are practically no magnetic substances. With the exception of the above, practically all other metals are **diamagnetic substances.** They are so named because if suspended between the poles of a magnet, instead of arranging themselves parallel with the magnetic lines of force, they take up a position at right angles to the magnetism, as though repelled by both poles. This property is of no practical value.

All substances may be classified magnetically as follows:

1. Magnetic substances; those which are attracted by a magnet.

2. Diamagnetic substances; those which are feebly repelled by a magnet.

3. Non-magnetic substances; those which are not affected by a magnet in any way.

Dr. Gilbert's greatest discovery was that the magnetic needle points north and south because the earth itself is a great magnet, Its poles coincide very nearly with the geographical poles and cause the suspended magnetic needle to take up a northerly and southerly direction.

If an iron bar is approached to the pole of a magnet, magnetic polarity is induced in the iron even before it actually comes in contact with the magnet. This may be shown by placing filings on the opposite end of the iron bar from that nearest the magnet.

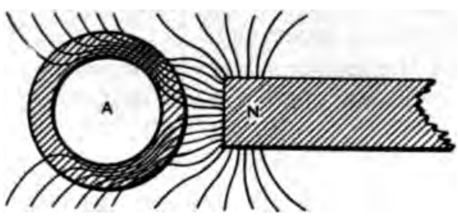


FIG. 95.

They will adhere to it even though it has not touched the magnet and has not previously been magnetized. This is known as **magnetic induction** and is very similar to the action of an electrified body on an unelectrified one. The pole in the iron nearest the pole in the inducing magnet will be of the opposite sign while the pole at the farthest end of the iron bar will be the same as the inducing pole. If the amount of magnetism induced in the bar is comparatively large the bar is said to possess high permeability.

Even though a sheet of glass, wood, paper or copper be interposed between the magnet and the piece of iron, magnetic induction will take place as though nothing were there. Magnetism acts across all substances. **There is no insulator of magnetism.** If, however, a hollow iron cylinder or sphere be approached to the pole of a magnet, magnetic lines of force will follow the

path through the iron and be deflected away from the interior. Thus, a needle, watch or other device, *A*, which it is desired to shield from magnetism will be protected by mounting it within an iron cylinder, as in Fig. 95. The cylinder does not act as an insulator of magnetism but serves to deflect the magnetism around the object because it offers a better conducting path. Non-magnetic watch protectors are simply iron cases neatly finished which will shield the hairspring of a watch from stray magnetic fields.

Some substances retain magnetism better than other substances. The softer and purer a piece of iron, the greater the amount of magnetism which can be developed in it but the shorter will be the time it will retain this magnetism after the magnetizing force is withdrawn. Cast iron and hard steel will not allow nearly as much magnetism to be developed in them, but they retain magnetism for a much longer time after the removal of the magnetizing force. This ability of metals to retain magnetism is known as **retentivity.**

On account of the similar actions of electrostatic charges and magnetic poles, it was quite natural that theories should be proposed in which magnetism would be accounted for on the ground that it was a fluid. It is certain, however, that whatever else it may be, it is not a fluid. When a magnet is rubbed on a piece of iron it magnetizes it without losing any of its original magnetism. It is impossible to imagine a fluid propagating itself indefinitely without loss.

SECTION IV CHAPTER I

MAGNETISM

HISTORICAL

1. What is lodestone? Where is it found and what properties does it possess?
2. What is the chemical expression for magnetite? Give the meaning of the symbols used.
3. What are the relative abilities of soft iron and hard steel for retaining magnetism?
4. What was Dr. Gilbert's greatest discovery?
5. Distinguish between the north and south magnetic poles of the earth and the north and south magnetic poles of a compass needle. By common agreement, which is the north or marked pole of a compass needle?
6. What is the first law of magnetism?
7. What is the difference between a magnet and a magnetic subject?
8. Give a list of the magnetic substances.
9. What is meant by a diamagnetic substance?
10. Give a list of the diamagnetic substances.
11. What is meant by a non-magnetic substance?
12. Give a list of the principal non-magnetic substances.
13. How may a body be shielded from magnetic lines of force?
14. Mention an experiment which shows the difference in action of charged bodies and magnets upon the magnetic needle and the needle electroscope.
15. Explain magnetic induction. Distinguish between the effects of electrostatic induction and magnetic induction.

MAGNETISM

CONSTRUCTION OF MAGNETS

The simplest method of making a steel bar magnet, or magnetizing a steel needle, is as follows: Take a powerfully magnetized bar magnet, *A*, Fig. 96, and approach one pole to the needle, *B-C*, which is to be magnetized. Stroke the needle from one end, *B*, to the other end, *C*. Then return the pole end of the magnet *A* through the air as shown by the arrows, to the end *B* of the needle. Repeat this stroking process about twenty times. This will develop a strong magnetic polarity in the needle. If the end of the needle, *C*, is last touched by the north pole of the magnet, *A*, then the needle will acquire a south pole at the end *C*, and a north pole at the end *B*.

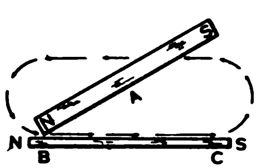


FIG. 96.

The most powerful magnets are electro-magnets. These are constructed of soft iron or steel cores around which are wound coils of insulated wire through which current is caused to circulate. Such magnets are capable of developing magnetic fields of much greater intensity than can be produced by permanent magnets.

Magnets are generally constructed in the form of bars, or in horseshoe shape so as to form as nearly as possible a closed magnetic circuit, Fig. 97. It has been found that long, thin magnets are more powerful in proportion to their weight than

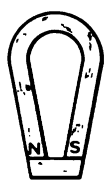


FIG. 97.

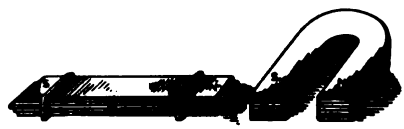


FIG. 98.

short, thick ones. In steel magnets the magnetism appears to reside upon the surface. If a steel magnet is immersed in an acid which will dissolve away the outer layer of steel, it will be

found to have lost the most of its magnetism. It is therefore customary to construct powerful magnets of thin laminations of steel, which have been separately magnetized and afterwards bound together as in Fig. 98. These are known as **compound magnets** and are much more powerful than solid bars of steel of equal cross-section. The permanent magnets in simple alternating current generators, called magnetos, are constructed in this fashion.

If a crowbar is inserted in the earth it will have magnetism developed in it by induction from the earth. The lines of force of the earth pass through it and induce a pole in the end sticking in the ground, opposite in sign to the pole at that end of the earth. Thus in this latitude a bar would have a north pole induced in the end in the ground. In southern latitudes a south pole would be induced in the end in the ground. If a bar of steel is held in a northerly and southerly direction and inclined slightly towards the surface of the earth and is then struck a sharp blow with a mallet it will develop a considerable amount of magnetism. This can be demonstrated by approaching the bar to a compass needle before being struck when it will act upon it but feebly and will attract either pole. After being struck, however, clearly defined and comparatively powerful polarity will be developed, which will act sharply on the compass needle. Reversing the position of the bar and striking it another blow will reverse the polarity. If the bar is held east and west and struck, no polarity will be developed. In this latitude all magnetic lines of force run more nearly vertical than horizontal. As a result all vertical iron columns are found to be magnetized with their lower ends north poles and their upper ends south poles.

After magnetism has once been developed in a bar, care must be taken not to subject it to jolts or knocks, as any vibration will tend to destroy the magnetism to a greater or less degree. While the magnetism is thus reduced it will never be completely destroyed unless the bar is heated to a temperature of about 700° C. Under these circumstances the magnetism will entirely disappear. It has also been found that cooling a steel magnet to 100 degrees below zero, centigrade, will destroy all traces of magnetism. But if steel is cooled to about 200 degrees below zero, centigrade, it will exhibit magnetic properties nearly twice as high as at zero. Even soft iron after being magnetized will

retain a small amount of magnetism when the magnetizing force has been withdrawn. This small quantity remaining is known as **residual magnetism.**

In the construction of magnets for electrical instruments great care must be taken in the preparation and hardening of the steel in order that the magnets may retain their magnetism indefinitely. Steel may be hardened in two ways. First, by suddenly cooling it from a high temperature. Second, by compressing it under hydraulic pressure, allowing it to cool slowly. If steel bars are heated to a bright red and then plunged into water, oil or mercury, they become very brittle and glass hard. If a magnet is to have a length which is less than twenty times its diameter it should be made glass hard in order to retain its magnetism. Magnets whose length is to be twenty or more times their diameter should have the temperature let down until the steel acquires a blue tint. This is accomplished by taking the glass hard steel and gently reheating it until it is very nearly red hot. It softens slightly under this process and eventually becomes blue in color. It is then quite springy and flexible.

If a magnet is to be of unvarying strength a shape should be chosen which will form a nearly closed circuit. The steel should then be hardened and tempered in accordance with the preceding instructions. It should then be placed in a steam bath at about 100° C. for twenty or thirty hours and then magnetized thoroughly after which it should be placed in the same bath again for five hours. This second immersion in steam will result in settling the magnetism to a value that will thereafter be practically permanent. If this were not done the magnetism would diminish gradually for some time after the magnet was put in use. Heating a magnet to any extent reduces the magnetism perceptibly although it partially regains its original strength on cooling. Heating a magnet, therefore, has the effect of decreasing its strength slightly.

When a magnet forming a closed circuit and supplied with keeper is first magnetized, it is found to possess more magnetism than it will manifest again after the keeper is once broken away from the poles. When a magnet has been magnetized as highly as possible it is said to be saturated, and when magnetized to a greater degree than it can retain it is said to be super-saturated.

The General Electric Company at their Lynn works magnetize

their permanent steel magnets for meters by slipping them over a massive copper bar about two inches in diameter. A number of magnets are strung along this bar. A current of 10,000 amperes under a pressure of three volts is passed through the bar for about three seconds. They are magnetized to full saturation in that time.

The Westinghouse Electric and Manufacturing Company magnetize their magnets for meters by a separable coil which fits around the magnet. A current of 250 amperes passes for a few moments. After the magnets are thus saturated, they are subjected to a coil carrying alternating current for the purpose of getting rid of the super-saturation, or, as it is called, "aging" them. This is a later method than the steam bath referred to above.

Strength of a Magnet

The strength of a magnet may be determined by the magnetic force which it exhibits at a distance upon other magnets. Thus, suppose there are two magnets acting upon a suspended needle. If at the same distance from the needle the two magnets produce equal deflections, their strengths would be equal. In other words, the strength of a magnet may be defined as the amount of free magnetism at its poles.

Lifting Power of a Magnet

A distinction must be drawn between the **strength** of a magnet and its **lifting power.** The lifting power of a magnet depends upon the shape of its poles and the number of lines of force passing through its poles. A horseshoe-shaped magnet with both poles connected by a soft iron keeper will lift three or four times as much as with one pole alone. A bar magnet will lift more or less depending upon the shape of the pole. Suppose there are three bars of equal magnetic strength, Fig. 99, and that there is the same amount of free magnetism at the poles of all three. If the end of the bar A flares out it will lift the least. If the pole of B is the same area as the bar, it will lift more. If the pole is chamfered off so that its face has a smaller cross-

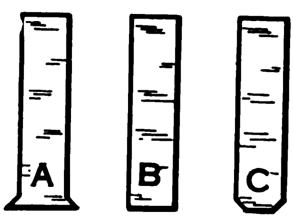


FIG. 99.

section than the bar, as in *C*, it will lift the most. The reason for the various lifting powers above mentioned, is found in the law which governs the lifting power of a magnet. This law states that **the lifting power is proportional to the square of the number of magnetic lines of force per unit cross-section.** Thus, if the pole be chamfered off until the area is reduced one-half, and the original amount of magnetism is crowded into this reduced cross-section, the density of the magnetism would be doubled. This would cause the lifting power for the reduced area to be quadrupled. As the cross-section, however, has been reduced to one-half, the lifting power is actually only doubled. Practically it would be found impossible to concentrate the magnetism to such an extent as to bring about this result. Nevertheless, the lifting power may often be increased to some extent by diminishing the cross-section of the pole.

The lifting power of a steel magnet will grow in a curious way. If the keeper be applied to a horse-shoe magnet, Fig. 97, and loaded to the maximum amount which it is capable of sustaining without breaking away, it will be found that it will sustain more if the keeper be left in contact for a day. This growth will continue for some time. If the keeper is once broken away, the lifting power will fall to its original value.

SECTION IV CHAPTER II

MAGNETISM

CONSTRUCTION OF MAGNETS

1. Explain the process of developing magnetism in a bar of iron by the stroking method.

2. How do long and short bar magnets compare as to their ability for retaining magnetism?

3. What shape should be chosen for a magnet in order that it shall retain its magnetism?

4. What is the object sought in making laminated or compound magnets?

5. What is the effect upon a bar of iron when placed in the magnetic meridian and struck a blow? What will be the effect of reversing its position and again striking it?

6. What is the result of dropping or jarring a permanent steel magnet? What is the effect of heating a permanent steel magnet?

7. What are the effects of extremes of temperature upon permanent magnets?

8. How should steel be hardened when preparing it for use in permanent magnets?

9. What treatment should steel receive after hardening in order to make magnets of unvarying strength?

10. How are permanent magnets magnetized?

11. How should magnets be "aged" after magnetization?

12. Define the strength of a magnet.

13. What determines the lifting power of a magnet? Explain the effect upon the lifting power resulting from an alteration of the pole shape.

MAGNETISM

MAGNETIC POLES AND THEORIES

A magnetic line of force is defined as an imaginary line in space along which magnetic force acts. The space around a magnet is filled with these magnetic lines. Taken as a whole, they constitute a magnetic field. This field is very intense near the poles of the magnet. The density of the magnetic lines or the intensity of the field becomes less as the distance from the pole increases. These lines of force radiate from a pole in every direction, Fig. 100. Magnetic lines are supposed to emanate from the north pole of a magnet, pass through space and enter at the south pole, continuing through the bar from south to north, Fig. 101. Therefore these lines really constitute closed magnetic circuits. If another magnet is approached to the one represented, the lines of force from the north pole of the large magnet will pass through space, enter the south pole of

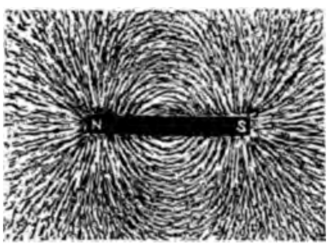


Fig. 100.

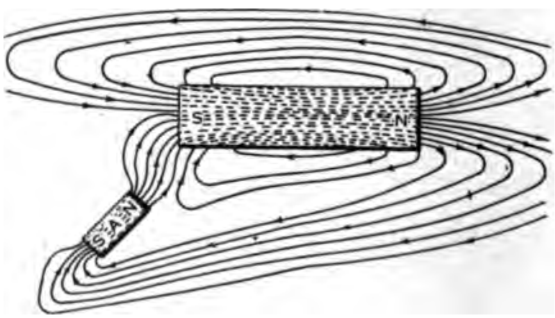


Fig. 101.

the smaller magnet, emanate from the north pole of that magnet and then return through the south pole of the large magnet. It is important to notice that magnetic lines of force **are closed loops of force** without beginning or ending.

Lines of force can be detected only in the space outside of a magnet. If the north pole of one magnet is placed in contact with the south pole of another magnet of equal strength, the lines of force emanating from the north pole enter the south pole and the magnetic field disappears. As a pole is simply that

FIG. 102.

portion of a magnet where the lines of force passing through it emerge into space, if opposite poles are placed in contact thereby causing the external field to disappear, the poles also disappear. That opposite poles do neutralize each other can be demonstrated by experiment. If a weight, such as a key, be attached to the north pole of a magnet, and a south pole is approached and brought into contact with this north pole, the key is instantly released, because the two poles neutralize each other.

When a bar of iron is uniformly magnetized, whether it be straight or horseshoe in form, it is said to possess salient poles. Fig. 101 illustrates magnets with salient poles. When two or more like poles unite to form a resultant pole the magnet is said to possess consequent poles. Fig. 102 shows consequent pole

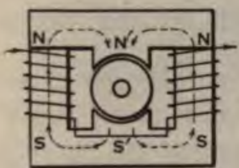


FIG. 103.—Consequent pole construction for generators.

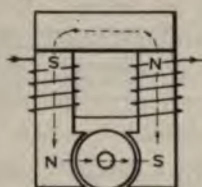


FIG. 104.—Salient pole construction for generators.

formations in a bar. Here lines of force emanate from the side of the bar at the point N, and return partly to the end marked S, and to another pole at the left marked S. These poles, S and N, are really the result of two like poles combining to produce a resultant pole. Generators sometimes employ structures of

this kind. Thus, Fig. 103 shows a design in which the upper terminals of both magnetic field coils are north. The lines of force combine to produce one large resultant north pole, N', which gives a uniform distribution of magnetic flux through the armature. Below this, another consequent south pole, S', is produced. The lines of force then divide and return to the respective coils where they were generated. Fig. 104 represents a salient pole formation wherein a single magnetic circuit is shown. The magnetizing coils in this illustration are magnetically in series, while the magnetizing coils in Fig. 103 are magnetically in multiple.

It has already been stated that when a magnet is broken up into several parts, each part will act as a complete magnet with two poles. Moreover, the strength of each portion of the broken magnet will be very nearly as great as the original magnet. If

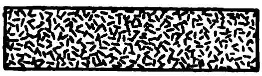


FIG. 105.—Chaotic arrangement of molecules in unmagnetized bar.

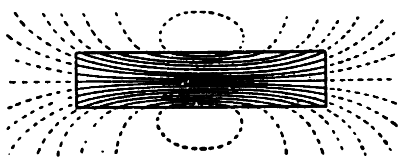


FIG. 106.—Uniform arrangement of molecules in bar of iron after being subjected to magnetizing force.

the broken parts are reassembled, the intervening poles will all disappear and only the original poles at the extremities will remain as before. Even though the magnet be broken into innumerable fragments, each particle will act as a magnet and exhibit polarity.

According to the commonly accepted theory of magnetism, each ultimate particle of a magnetic substance is, and always has been, a magnet. Before the bar is magnetized, the molecules are arranged in a chaotic manner satisfying each other's attractions and repulsions by various arrangements, as suggested in Fig. 105. The process of magnetization simply consists in bringing a superior magnetizing force to bear upon the bar. This will cause all of the north poles of the molecules to be attracted in one direction, while the south poles are repelled in the opposite direction.

The molecules are thus straightened out from their original

chaotic condition, Fig. 105, and are made to arrange themselves in parallel lines, all the north poles pointing to one direction, and all of the south poles pointing in the opposite direction, Fig. 106. If the material is hard, as in the case of steel, a certain molecular rigidity causes these particles to remain in line once they have been arranged in this way. A surface made up entirely of north ends of molecules constitutes a north pole. A surface composed of south ends of molecules constitutes a south

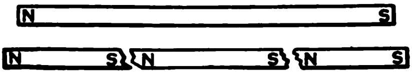


FIG. 107.

pole. If a bar is broken, Fig. 107, one surface will consist of the south ends of the molecules while the other surface will consist of the north ends, for it is not possible to divide the molecules by mechanical means. Magnetization, therefore, is an action affecting the arrangement of the molecules. The process of magnetization simply consists in developing within a bar a force that was resident therein but was not manifested externally. Magnetizing a bar does not consist in transferring from the magnet to the bar any force or energy, but is simply the development of a force that has always been inherent therein.

Joule found that an iron bar increases in length when strongly magnetized. Bidwell found that still stronger magnetizing forces caused the iron to subsequently contract. This shows

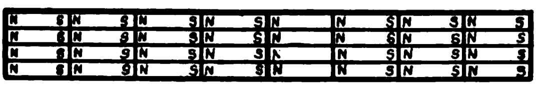


FIG. 108.

that the molecules as they turn over, cause the bar to first expand and then as they settle into position, eventually contract.

If a test tube be filled with glycerine in which iron filings are stirred, and the tube subjected to a longitudinal magnetizing force, the particles will line up in such a way as to allow light to pass lengthwise through the tube and contents, although not permitting the light to pass across the direction of magnetization. If a bar of iron is suddenly magnetized or demagnetized, a faint metallic clink is heard. If a bar is rapidly magnetized,

first in one direction and then the other, it will give out a decided hum. If a bar is rapidly magnetized first in one direction, then in the other, it will grow hot, due to grinding of the molecules against each other as they turn first in one direction and then in the other. All of these mechanical effects, namely, expansion and contraction, production of sound, production of heat, and lining of the particles, as in the test tube, support the theory that **magnetism is an action affecting the arrangement of the molecules.** A magnetized bar, then, is simply a bar in which the molecules have been systematically arranged with their north poles all pointing one way and their south poles all pointing the other way, as in Fig. 108.

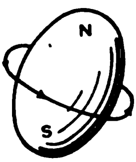


FIG. 109.

Ampere undertook to account for the magnetism of a molecule by supposing that all magnets were electro-magnets, and that each molecule of iron was a magnet by virtue of a minute electrical current, which circulated ceaselessly around it in a path of no resistance, Fig. 109. This current flowed continuously, presumably because there was no resistance offered to its flow. But Ampere did not suggest the origin of the current.

Now it seems that there is ample evidence that every molecule of matter, in fact every atom which goes to make up the molecules of matter, is composed exclusively of millions of electrical charges or ions, and that these electrical charges move with great speed in definite paths, or micro-astronomical orbits about an electrical center possessed by each atom.

In other words, each atom is in reality a planetary system on a Lilliputian scale, and the ions are the planets, completing millions of orbital revolutions within a second of our time. It is a well-known fact that electrical charges in motion will produce the same magnetic effect as electrical currents. Consequently the whirling ions in their orbital movements constitute the electrical currents proposed by Ampere. Now, if the orbital revolutions of the ions are formed of both positive and negative charges, equal in amount and traveling in the same direction, the magnetic effect upon the atom or planetary system as a whole may be trivial or nil, because of the neutralizing tendency of the ions of opposite signs. But if there be an excess of either positive or negative ions, and if they travel in the same direction, the

natural result will be a permanent magnetism in the atom. If the excess of positive or negative ions be small and they travel in the same direction, the magnetic effect may be slight, as in nickel, but if the positive and negative ionic charges travel in opposite directions in large orbits, or if the ions of one sign greatly exceed those of the opposite sign, the magnetic effect may be great, as in iron.

The atomic weights of iron, nickel and cobalt (the magnetic metals) are 56, 58.7 and 59, respectively; that is, their relative weights as compared with atoms of hydrogen. Now, it is supposed that the vortical movements of the ions in these substances are of the proper adjustment to produce a permanent magnetic field at relatively great distances, compared with the size of the orbits, or even the size of the atom. The fact that the atomic weights of these powerful magnetic substances lie so closely together suggests that the vortical orbital motion of the ions is intimately associated with the atomic weight.

Heusler produced an alloy of three substantially non-magnetic metals, namely, manganese, aluminum and copper. This alloy is almost as magnetic as nickel, and indicates the possibility of associating atoms of different substances in such a way that although the magnetizing influence of the ions in each atom may be almost zero, the resultant molecular magnetizing influence of the mixture may be considerable. Upon this theory it is hoped that by some simple process or treatment, the magnetic properties of iron may be exceeded artificially or some alloy of even greater magnetic properties may be made.

This ionic theory points to the idea that all matter is composed of atoms and all atoms of moving ions, and all ions being nothing but individual electrical charges, all matter may therefore be nothing but organized electricity. If this be true, then matter is nothing but energized electro-magnetic ether, and the universe contains but two entities, the all-pervading ether and the energy residing therein, matter being a particular form of energy.

SECTION IV CHAPTER III

MAGNETISM

MAGNETIC POLES AND THEORIES

1. Define a magnetic line of force. What constitutes a magnetic field?
2. Explain the nature of magnetic lines of force. From whence do they emanate and where do they terminate?
3. Define salient magnetic poles. Sketch.
4. Define consequent magnetic poles. Sketch.
5. What are some of the mechanical effects of magnetization? What do these effects indicate?
6. Explain the molecular theory of magnetism.
7. What is the effect of breaking a magnet? Can a magnet be constructed with only one pole?
8. Explain Ampere's theory of magnetism.
9. Explain the Ionic theory of magnetism.
10. Is it possible to construct a magnetic alloy from non-magnetic components?

SECTION IV CHAPTER IV

MAGNETISM

TERRESTRIAL MAGNETISM

Laws of Magnetism

The first law of magnetism is: **Like poles repel each other, unlike poles attract each other.**

The second law of magnetism is: **The force exerted between two magnetic poles varies directly as the product of their separate strengths and inversely as the square of the distance between them, provided the distance is so great that the poles may be regarded as mere points.**

These laws are practically identical with the first two laws of static electricity.

Measurement of Magnetic Force

Magnetic force may be measured in four ways. First, the oscillation method. In this method a magnetic needle, *A*, Fig. 110, is set swinging, in the magnetic meridian under the influence of the earth's magnetism. The needle will obey the law of pendular vibration which is, "the square of the number of oscillations executed in a given time is proportional to the force." Suppose that a magnetic needle performs 13 oscillations in a minute. The force would be proportional to the square of 13, or 169. Next, suppose a permanent bar magnet be approached so that the south pole is within 5″ of the north pole of the needle as in *B*. Again set the needle swinging. The forces acting on the needle are now the combined forces of the earth's magnetism and the permanent steel magnet. Suppose that the needle now oscillates 22 times. The force is proportional to the square of 22, or 484. In order to get the effect of the permanent magnet's force without the earth it is necessary to deduct 169, which is proportional to the force of the

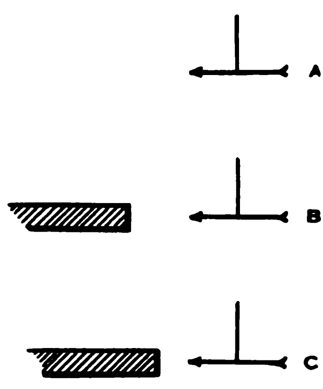


FIG. 110.

earth's magnetism, from 484, which is proportional to the sum of the earth's magnetism and that of the permanent magnet at 5″, which leaves 315. If now the magnet is moved up to 2½″ from the needle, as in *C*, the needle will oscillate about 38 times in a minute, $38^2 = 1{,}444$. Deducting from this quantity 169, which is a measure of the earth's magnetism, we have 1,275. The force of the permanent magnet at 5″ is proportional to 1,275. 1,275 is approximately 4 times 315. As the distance between the magnet and the needle has been halved, the force has been quadrupled, which is a proof of the second law of magnetism.

Light, radiant heat and magnetism, in fact, all forms of radiant energy, obey this law. If a rectangular opening, *a*, 1 foot square is placed at a distance of 3 feet from a candle, *L*, Fig. 111, and a

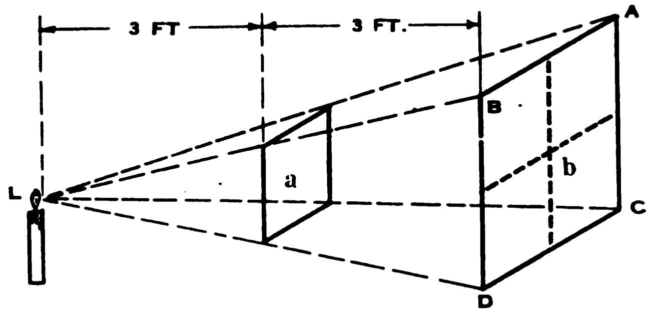


FIG. 111.

screen, *b*, is placed at a distance of 6 feet from the candle, it is evident that the light passing through the first opening will be distributed over a space on the screen which is twice as broad and twice as high as the first opening. In other words, it will be distributed over four square feet. The intensity of the light, therefore, on one square foot of surface will be one-fourth as great on the larger screen as it was in the smaller opening. This is an illustration of the law of the inverse square, namely, that at twice the distance from the source, the intensity of the light is one-fourth as great.

In performing the experiment for determining the strength of a permanent magnet by the oscillation method, the bar should be long enough so that one pole could be placed centrally over the needle, as in Fig. 112, and thereby have its effect on the two poles of the needle neutralized. The measurement of forces

by this method is simply comparative. The force is not measured in definite units.

The second method of measuring magnetic force is the deflection method. In this case a permanent magnet is approached to a suspended needle and the degree of deflection produced by the magnet is observed. This will be a measure of the force present. The position of the deflecting magnet should be as in Fig. 112.

The third method of measuring magnetic force is the torsion method. In this case the needle is suspended by a silver or phosphor bronze wire from a screw called the torsion head, Fig. 113. A magnet is brought to bear on the suspended needle which causes it to deflect. By taking hold of the torsion head and turning it against the deflecting force it will be possible to

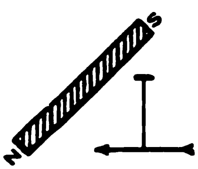


FIG. 112.

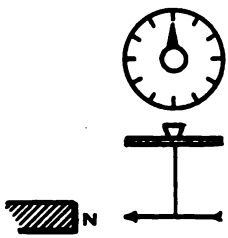


FIG. 113.

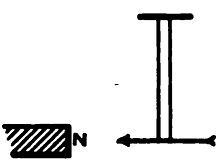


FIG. 114.

bring the needle back to the starting point, at which time the force of torsion is balanced against the deflecting force of the magnet. A pointer on the torsion head moves over a scale on top of the apparatus and indicates di ectly the degrees of torsion. The force is strictly proportional to the angle through which the index has been turned in order to restore the needle to the starting point.

The fourth method of measuring magnetic force is by the bifilar suspension. In this case the needle is suspended by two parallel fibers as in Fig. 114. When a magnetic force is brought to bear upon the needle it is deflected, thereby twisting the two fibers and raising the center of gravity. It is really a gravity method.

A **magnetometer** is a sensitive arrangement of magnetic needles for detecting slight changes in the earth's magnetism. It consists of several small pieces of watch spring magnetized

with all of their north poles pointing in one direction and glued to the back of a small silvered mirror, the latter being suspended in a frame by a single strand of cocoon fiber, Fig. 115. A beam of light is thrown on the mirror and is reflected on a screen placed about 3 feet from the mirror. Any slight movement of the needle will cause a magnified movement of the beam of light on the screen. This light beam constitutes a weightless pointer which will very readily show slight movements of the needle, otherwise impossible to detect.

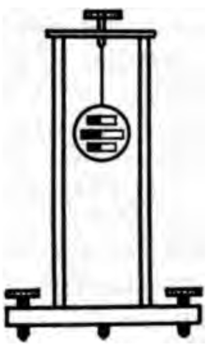


FIG. 115.
Magnetometer.

Unit Pole

A unit strength of magnetic pole is defined in a manner similar to that for a unit quantity of electricity. That is, **a unit magnetic pole is one of such a strength that when placed at a distance of one centimeter in air from a similar pole of equal strength, it repels it with a force of one dyne.**

Terrestrial Magnetism

The north magnetic pole of the earth is situated about one thousand miles away from the geographical pole at a peninsula extending from Canada, known as Boothia Felix, just within the Arctic Circle. It was located by J. C. Ross in 1831. The south magnetic pole of the earth has never been located, but from the distribution of the magnetism in southern latitudes there appear to be two south polar regions. The magnetic masses in the earth are distributed somewhat as illustrated in Fig. 116. As a result of this distribution of the magnetic material in the earth, the compass needle does not point geographically north and south at all points of the earth's surface. Thus at Washington the magnetic needle points about 6 degrees west of true north. Its angle between the magnetic meridian and the geographical meridian of a place is called the **declination** of that place. The

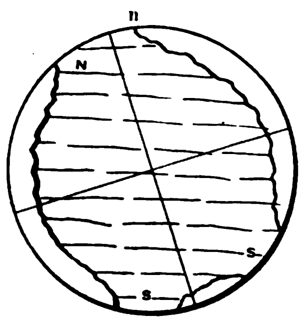


FIG. 116.—Distribution of magnetic masses in earth.

existence of that declination was discovered by Columbus in 1492, though it appears to have been previously known to the ancients. When Columbus traveled so far around the earth's surface that the geographical pole and the magnetic pole were no longer in line with each other, the needle which at *A*, Fig. 117, originally pointed to the magnetic north *N* through the geographical north, *n*, now at *B*, declined decidedly to the west as illustrated. In order that vessels may navigate by the compass, magnetic charts have been prepared on which the declination of the needle at different places is carefully noted.

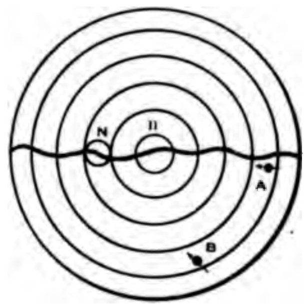


FIG. 117.

In 1576 an instrument maker named Norman discovered that a steel needle which he had constructed with great care, balanced on a horizontal axis, tended to dip downward toward the north immediately after it was magnetized. He then constructed a dipping needle capable of turning about in a vertical plane around a horizontal axis. Such a needle will incline from the horizontal toward the perpendicular about 70 degrees at Washington. This is because the magnetism comes upward through the earth's surface at an angle instead of going out from the poles perpendicularly. As the lines of force pass from the north pole to the south, however, they would be parallel with the earth's surface at the equator, and the needle would not dip at all at that point. In southern latitudes, however, the south pole of the needle would dip downward.

The declination of the magnetic needle and also the dip or inclination vary at different points on the earth's surface. Charts have been prepared which show the inclination as well as the declination of the compass needle.

Running from north to south through both hemispheres is a line at any point upon which the magnetic needle will point to the geographical north. This is called the **Agonic line** or the line of no declination. This is the line shown across the chart in Fig. 117. On either side of this line are points where the magnetic needle will decline a certain number of degrees to the

east or west. A line drawn through all places connecting points of equal declination would be called an **Isogonic line.** Charts upon which isogonic lines showing all the various declinations are plotted are called **Isogonic charts.** These lines are quite irregular, but their general direction is north and south, Fig. 118.

It is possible to plot a line around the earth from east to west at all points upon which a magnetic needle will remain perfectly horizontal. Such a line would be called the **magnetic equator.** If we connect with a line all points around the earth upon which the magnetic needle dips downward to the north an equal number of degrees, such a line would be called an **Isoclinic line.** Charts upon which these lines of equal magnetic inclination are mapped

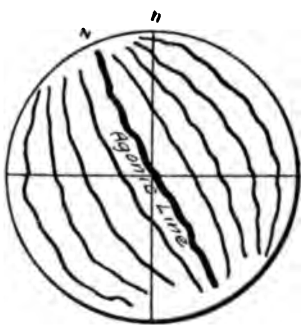


FIG. 118.—Isogonic chart.

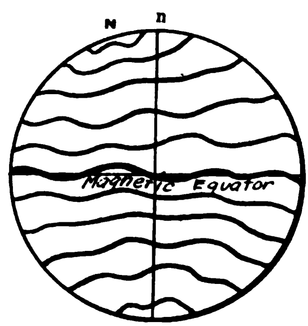


FIG. 119.—Isoclinic chart.

out are called **Isoclinic charts,** Fig. 119. Isoclinic lines are as irregular as isogonic lines but their general direction is east and west.

The earth's magnetism is constantly undergoing changes. Some of these changes occur quickly while others occur very slowly. Changes which require many years to run their course are called secular changes. When magnetic observations were first made and recorded, it was found that the compass needle at London pointed 11 degrees to the east of true north. This declination gradually diminished and in 1657 the needle pointed true north at that point. It then moved west until the year 1816 when its total declination was 24 degrees, after which time it slowly moved backward. It is estimated that by the year 1976 it will again point true north, making a complete cycle of change in about 320 years. By carefully observing the changes in the earth's magnetism by means of the sensitive magnetometer

above referred to, it is found that the compass needle commences to move westward at about 7 o'clock each morning and continues its travel until about 1 p.m., after which it moves slowly backward until about 10 p.m., after which it is stationary. These daily variations never exceed more than 10 minutes of arc. The magnetism of the earth is affected by the position of the sun and also of the moon. Magnetic variations also occur annually and at intervals of about eleven years. The maximum disturbances which occur at eleven-year intervals coincide with the appearance of sun spots.

In addition to the regular changes in the earth's magnetism there are irregular disturbances which occur occasionally over the earth's surface. These are known as magnetic storms. They occur simultaneously with "earth currents" which sometimes seriously disturb telegraph systems employing grounded returns. Whether the magnetic disturbances produce earth currents or the earth currents produce the magnetic disturbances, is not known, but they are in some way connected.

Several theories have been proposed to account for the earth's magnetism. It is known that the evaporation going on at the earth's surface, especially in the tropics, causes currents of heated air to be electrified positively with respect to the earth. These air currents travel northward and southward toward the cooler polar regions, where they descend. These streams of electrified air act like true electric currents and as the earth revolves within them it becomes an electromagnet. Sylvanus Thompson believes that this is the only way in which the earth's magnetism could possibly have grown to its present state.

Another theory proposes that the earth is magnetized by direct induction from the sun. As the sun is 93 millions of miles from the earth, the length of the circuit through which the magnetic lines would have to travel would be approximately 3 times this amount, or 280 millions of miles. It is highly improbable that the lines of force of the sun could ever have induced the high magnetic condition which the earth now possesses. Nevertheless there is evidently some direct connection between the sun's magnetism and the earth's magnetism. Whenever a sun spot, which is an outburst of solar energy, is observed through the telescope, there is simultaneously observed a disturbance of the magnetic needle.

SECTION IV CHAPTER IV

MAGNETISM

TERRESTRIAL MAGNETISM

1. Explain the oscillation method of measuring magnetic force. What does it prove? Explain by the aid of a light beam, the identity of the law governing magnetism and the law governing light.
2. Explain the deflection method of measuring magnetic force.
3. Explain the torsion method of measuring magnetic force.
4. Explain the construction of a magnetometer. For what is it used?
5. Indicate by a sketch the relative positions of the geographic and magnetic poles of the earth. Where is the north magnetic pole located?
6. What is meant by the "declination" of the compass needle? What is the Agonic line?
7. What is an Isogonic line? What is an Isogonic chart?
8. What is meant by the "dip" of the magnetic needle?
9. What is an Isoclinic line? What is an Isoclinic chart?
10. What is a magnetic storm?
11. Is the magnetism of the earth stable? If subject to variations, when do these variations occur?
12. Explain the generally accepted theory of the earth's magnetism.

ELECTRO-MAGNETISM

MAGNETIC ACTION OF CURRENTS

The relation of static charges of electricity to each other has already been shown. The nature of electrical currents has been studied. Magnetism and the accompanying phenomena were discovered independently. It will now be wise to consider the relations existing between electricity and magnetism.

Some connection between these two sets of phenomena had long been suspected. Lightning had been known to magnetize steel bars. All attempts to duplicate these effects, however, by sending powerful currents through them, were unsuccessful. The discovery of the exact relation existing between electricity and magnetism was due to Oersted, of the University of Copenhagen, who in 1819 observed that a compass needle was affected

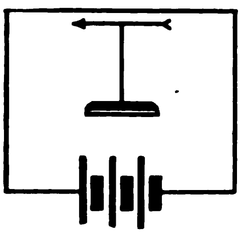


FIG. 120.

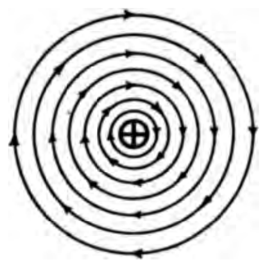


FIG. 121.—Flux about wire carrying current.

by a voltaic pile. Pursuing this discovery, he found that if a wire carrying a current was placed parallel with and immediately above or below a compass needle, as in Fig. 120, the needle would be deflected. He also found that the direction of the deflection depends upon the direction of the current. Thus, if the current passes from north to south over the needle the north pole of the needle is deflected east. The word NOSE will help to fix this rule in mind. Thus, if the current passes from "North" "Over" the needle to "South," the needle is deflected "East." He found that this deflection was due to the fact that there is a magnetic field around every wire carrying a current, and this magnetic field consists of closed loops or rings of magnetic force

surrounding the wire as in Fig. 121. Here, a wire, represented by the small central circle, is supposed to be carrying a current away from the observer through the paper. The cross illustrates the feathered end of an arrow to indicate the direction of the current. Around this wire, squarely at right angles thereto, are the magnetic whirls which constitute the field of force. These magnetic loops are most dense close to the wire and the intensity becomes less as the distance from the wire increases. The practical limit to the field is but a short distance from the wire, although theoretically the field extends a great distance into space.

It is impossible to have a current in a wire without having a magnetic field around the wire. In fact, some scientists state that it is impossible to refute the proposition that what is termed a current in a wire is nothing more than this whirl in the ether about the wire. From this viewpoint, the electrical transmission of power is not accomplished through the conducting wires of the electrical circuit, but the wires merely serve to point the way. The real transfer of energy is via the ether around the wire. Electrical power transmission, then, may be accomplished by creating a whirlpool, a vortex, in the ether, and the amount of power transmitted is proportional to the intensity of this field.

Direction of Flux

The direction of the current in the wire and the resulting field of force about the wire are related to each other as are the forward travel and right-handed rotation of a screw. Thus if in Fig. 122 the arrow on the straight wire represents the direction of the current, then the arrow, A, represents the direction of the magnetic field around it. The clock rule is another way of remembering this relation. Suppose the current is passing away from the observer through the stud that supports the hands of a watch. Then the magnetic whirl will be in the direction in which the hands move.

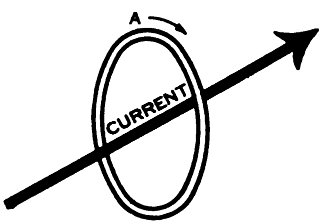


FIG. 122.—Relative direction of current in wire and flux about wire.

If parallel wires, A and B, Fig. 123, carry current in the same direction, the magnetic field around the two wires is in the same

direction, but if the lines of force around A encounter the lines of force around B at the points C-D, they repel each other. Now no two lines of force can meet or intersect. The result is, the line C is deflected in the direction E and the line D is deflected in the direction F. They then add themselves in series and the field between the two wires disappears. The tendency of magnetic rings or loops of force is to shorten themselves. They behave like a rubber band under tension. The contracting tendency results in drawing the wires A and B together. Thus a rule may be established that **parallel wires carrying currents in the same direction attract each other.**

Suppose a wire, A, carrying a current away from the observer forms a loop and returns through the wire B, Fig. 124, where the dot in the center of B pictures the point of an arrow indicating

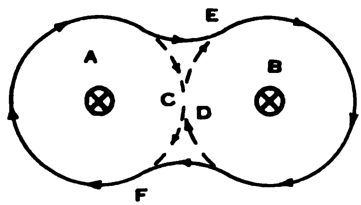


FIG. 123.—Wires carrying currents in the same direction attract each other.

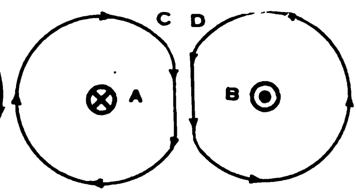


FIG. 124.—Wires carrying currents in opposite directions repel each other.

that the current is being carried toward the observer. The directions of the magnetic fields about these two wires are opposite the one to the other. The rings of force now approach each other at C-D, where they are deflected downward and crowd between A and B. This increased density of magnetic field between the wires forces them apart. Thus the rule may be established that **wires carrying currents in opposite directions repel each other.** The force of repulsion with large currents is very marked. In one instance a short circuit occurred in one of twelve alternators in a large Central Station System, consisting of twelve machines of several thousand horse power, operating in parallel. When the short circuit occurred these machines simultaneously pumped an enormous amount of energy into the short circuit. The cables leading from the machines to the switch-boards passed through a vault where wires of opposite polarity were separated a short distance from each other. The intensity of the magnetic repulsion in these cables produced a

result similar to that of an explosion. The cables were forced apart with such violence as to completely destroy a substantial brick wall which separated them from an adjoining room. In another instance the magnetic effect due to short circuit was so great upon a certain system of cables that they became so twisted together that they could only be untwisted with the aid of crow-bars.

High tension transmission lines of opposite polarity carrying wires suspended from a series of insulators are often caused to repel each other with such violence under the effect of a short circuit that they are forced outward until they whip out and up over the suspending cross-arms where they lodge until taken down.

Maxwell's Rule

Maxwell, after studying the magnetic effects of wires carrying currents, summed up these actions in the following way: **Every electrical circuit is acted upon by a force which urges it in such a**

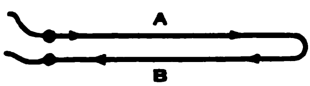


FIG. 125.

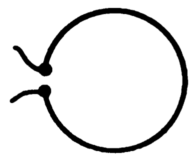


FIG. 126

direction as to cause it to include within its embrace the greatest possible number of lines of force. Thus, suppose a circuit is doubled back upon itself, as in Fig. 125. The magnetic whirls around the wire *A* will be in one direction while those around *B* will be in the opposite direction. As these lines of force crowd down between the two wires as in Fig. 124, the wires would be forced apart so that the circuit, if free to move, would assume the form, Fig. 126. This loop would evidently include within its embrace the greatest possible number of magnetic lines of force, while the close proximity of the wires *A* and *B* in Fig. 125 would permit very little flux to pass between them. A paraphrase of Maxwell's rule is this: **Every electric circuit tends to so alter its shape as to make the magnetic flux through it a maximum.** This rule explains the action of every electric motor and of many electric measuring instruments. In every motor there is a loop of wire carrying a current, said loop being placed in such a position in a magnetic field that the lines of force of the

field pass parallel to, but not through it. In obedience to Maxwell's rule the loop tends to turn in an attempt to include within its embrace the lines of force of the field. This action is repeated successively by every coil on the armature of a motor.

Galvanoscope

If a current is led through a wire over a needle as in Fig. 127, and then conducted back under the needle, the magnetic effect

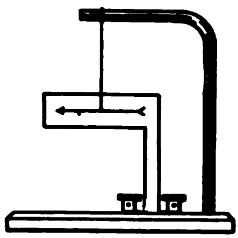


FIG. 127.—Simple galvanoscope.

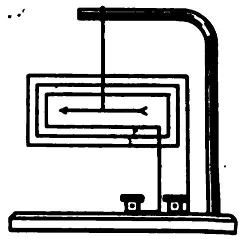


FIG. 128.—Multiplying effect of many convolutions of wire.

is doubled. A device of this sort is called a **galvanoscope.** This is a simple detector of an electric current, just as an electroscope is a detector of electric charges. If the current, instead of being passed around the needle once, is carried around it a number of times, as in Fig. 128, the magnetic effect is increased in proportion to the number of times the current is carried around. If the coil possesses 100 turns the effect will be 100 times as great as if the coil had but one turn. This device is called a **multiplier.**

Solenoid

The magnetic effects of successive convolutions of wire are made to add themselves as shown in Fig. 129. Here a coil is pictured, cut longitudinally with the front half removed. The currents in the successive convolutions are all in the same direction. Thus, the conductors in the upper half of the figure all carry currents away from the observer. The magnetic whirls about these wires are right-handed as in Fig. 123. They add themselves in series, passing through the core from *A* to *B*, where they emerge in space, completing the

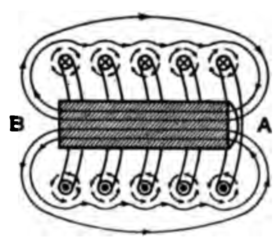


FIG. 129.

circuit through the air. From the observer's standpoint the lower ends of these conductors all carry current forward and the magnetic field is in the opposite direction. This causes these loops of magnetic force to also circulate through the core from A to B, completing the circuit through the air. Such a coil is called a **solenoid** and behaves like a magnet having a north pole

FIG. 130.—Solenoid.

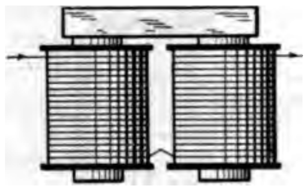


FIG. 131.—Electromagnet.

at B, where the lines emanate, and a south pole at A, where they reenter the coil. A solenoid in practice usually takes the form shown in Fig. 130, and is generally provided with a movable iron core. A solenoid is sometimes called an **helix,** although this latter term is not now commonly used. When a coil has a fixed iron core it is termed an electro-magnet; a common form employing two coils connected electrically in series and producing magneto-motive-forces likewise in series is shown in Fig. 131.

A circuit doubled back upon itself produces no external magnetic field. The magnetizing forces are always present but the magnetizing forces of one wire counteract the magnetizing forces of the other wire.

SECTION V CHAPTER I

ELECTROMAGNETISM

MAGNETIC ACTIONS OF CURRENTS

1. What was Oersted's discovery of the relation between electricity and magnetism?
2. In what direction will a compass needle be deflected if a wire carrying a current is brought near it?
3. When power is transmitted by electrical means what is the actual medium of transmission?
4. Give the right-handed screw rule for the relation existing between the flow of current in a wire and the resulting magnetic field around it.
5. Explain fully the relative direction of the magnetic field with respect to the current; the relative density of this field and its practical limit.
6. Give the clock-rule for remembering the direction of a current and its resulting magnetic field.
7. What happens to magnetic lines of force produced in the same region from separate sources, when they tend to conflict as to direction?
8. What is the magnetic effect of two currents flowing in the same direction in parallel wires? Sketch.
9. What is the magnetic effect of two currents flowing in opposite directions in parallel wires? Sketch.
10. State "Maxwell's rule" concerning the magnetic effect of a current in an electrical circuit.
11. What is a Galvanoscope?
12. How may the magnetic effect of a current be multiplied?
13. Define a solenoid. Sketch.
14. Define an electromagnet. Sketch.

ELECTRO-MAGNETISM

LAWS GOVERNING MAGNETIC CIRCUITS

Magnetic lines of force flow in any material capable of conducting them, in somewhat the same manner as an electrical current flows in a conducting circuit. The total flow of current in a wire is measured in **amperes.** The flow of magnetism is called the **flux** and is measured in **Maxwells.** The Greek letter Φ (Phi) is used to designate the flux in Maxwells, just as the letter I is used to designate the electric current in amperes. Another unit is employed to designate the flux density, or number of lines of force per square centimeter. This is called the **Gauss,** and is represented by the letter B. The relation of the flux density to the total flux may be illustrated in Fig. 132. Assume a bar 2 centimeters square containing 4 square centimeters; let the number of lines of force passing through one square centimeter be 10,000; the flux density is then said to be 10,000 Gausses, or 10 Kilogausses. If now the flux density, B, is multiplied by the cross-section, s, the total flux in Maxwells will be:

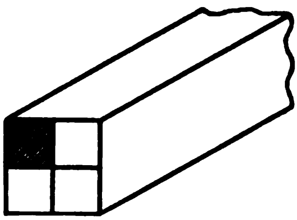


FIG. 132.

$$B \times s = \Phi; \text{ or } 10{,}000 \times 4 = 40{,}000 \text{ lines of force.}$$

The force which produces the magnetic lines is called the **magnetizing force.** Practically, this consists of a coil of wire carrying a current. It is represented by the letter H. One unit of magnetizing force, H, will produce one magnetic line of force, B, per square centimeter in air.

The permeability of a substance is its magnetic conductivity. That is, its relative ability to conduct magnetism compared with air as a basis. It is represented by the Greek letter μ (mu). The permeability of air is one. Permeability is the **ratio of magnetization to magnetizing force.** Thus

$$\text{Permeability} = \frac{\text{Magnetization}}{\text{Magnetizing force}}, \text{ or } \mu = \frac{B}{H}.$$

In air, B always equals H, therefore any value of B, divided by the same number, H, will equal one, which is the permeability of air.

$$\frac{B}{H} = \mu = 1.$$

Suppose a current is passed through a solenoid from a battery, Fig. 133. The magnetic lines of force will cause a suspended

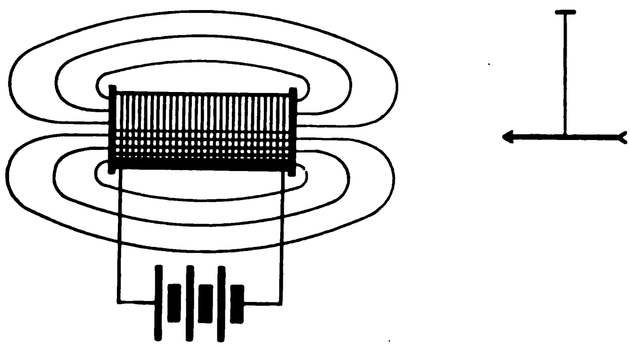


FIG. 133.

magnetic needle mounted nearby to be deflected. If, now, the solenoid is provided with an iron core, Fig. 134, and the same current as before is sent through it, the needle will be deflected much farther, although the same magnetizing force has been

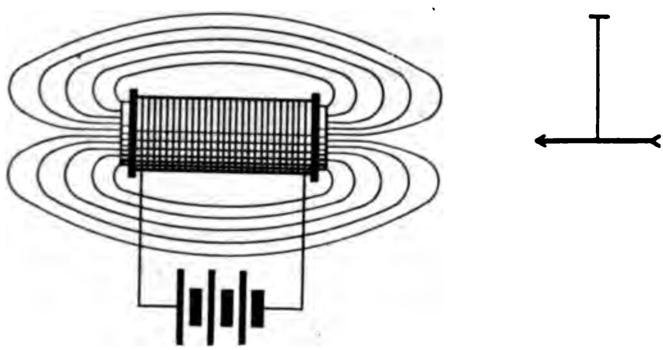


FIG. 134.

applied. This is because the resulting magnetic flux has been considerably increased. Suppose that in the first case the application of 100 units of magnetizing force, H, produced a

flux density, B, of 100 lines of force per square centimeter. The permeability of the air would be

$$\frac{B}{H} = \mu = \frac{100}{100} = 1, \text{ which is always true.}$$

Now suppose that by the application of the same 100 units of magnetizing force the result in the second case is 40,000 lines of force per square centimeter. The permeability of the iron core will be:

$$\frac{40{,}000}{100} = 400.$$

This means that the iron conducts 400 times better than air.

Strength of a Magnetic Pole

There are two ways of indicating the strength of a magnetic pole. First, by the number of unit poles it contains. Second, by the number of lines of force coming out of it. The strength of a magnet expressed in one set of units may be reduced to the other in the following way: A unit strength of pole may be considered as a point which sends out enough lines of force to produce a flux density of one magnetic line to every square centimeter of a surface situated one centimeter distant from the pole. There will then be as many lines of force concentrated at the pole point as there are square centimeters on the surface of a sphere of one centimeter radius. Now such a sphere has a surface area of 4π square centimeters (12.57 square centimeters). Therefore, **every magnetic pole** of **unit strength** has 4π **lines** of force **emanating from,** or **entering into it.**

A magnet with a strength of 15 unit poles will have $15 \times 4\pi$ or 189 lines flowing out of the north pole, passing through space and re-entering the south pole.

It has been found that if a solenoid is wound so that there is one turn of wire to each centimeter of length of the solenoid, and one ampere of current passes through the wire, the intensity of the magnetic field in the air inside of the solenoid is 1.257 gausses. This is because one ampere is $\frac{1}{10}$ of an absolute unit of current. It will, therefore, produce $\frac{1}{10}$ of an absolute unit strength of magnetic pole. A unit strength of pole must have 12.57 lines running through it. $\frac{1}{10}$ of this will be 1.257 lines per square centimeter cross-section of solenoid.

It must be observed that this flux density is independent of the diameter of the coil. The same 1.257 gausses will be produced on each square centimeter of cross-section whether the coil be one inch in diameter or three or four inches in diameter.

Intensity of Magnetizing Force

In an electro-magnet the actual magnetizing force is a current circulating in a coil of wire. The intensity of this magnetizing force per centimeter of length is expressed by the following equation:

$$H = \frac{4\pi IN}{10l}, \text{ or } \frac{1.257\,IN}{l}.$$

Where H = Intensity of magnetizing force per unit of length.
I = Current in amperes.
N = Number of turns in coil.
l = Length of solenoid in centimeters.

Total Magnetizing Force

The total magneto-motive-force in a circuit is the product of the intensity of the magnetizing force per unit of length, H, and the length of the magnetic circuit, l, in centimeters. The unit of magneto-motive-force is the **Gilbert,** and the symbol is the letter F.

Magnetic Reluctance

Just as an electric circuit offers resistance to the flow of a current, so a magnetic circuit offers resistance to the flow of magnetic lines. The resistance of a magnetic circuit is called reluctance and is expressed in **Oersteds,** for which the symbol is the letter R.

The calculation of magnetic reluctance, like the resistance of an electric circuit, would be comparatively simple were it not for a peculiar tendency of iron to saturation. That is, the permeability is not constant, but changes with every change in flux density. Thus, while the permeability of a piece of cast iron with a flux density of 4,000 lines per square centimeter is 800, it is found that when the flux density is increased to 5,000 lines, the permeability falls to 500. The reluctance in any case then will depend upon the flux density. The permeability for different kinds of iron, under various flux densities, has been calculated. The results obtained from one set of observations for a certain quality of wrought iron are given in the following table:

B	H	μ	B	H	μ
1,000	0.48	2,080	9,000	2.95	3,050
2,000	0.61	3,280	10,000	4.32	2,310
3,000	0.78	3,850	11,000	6.70	1,640
4,000	0.92	4,340	11,500	9.46	1,220
5,000	1.08	4,620	12,000	12.40	953
6,000	1.20	5,000	12,500	16.00	781
7,000	1.40	5,000	13,000	23.80	546
8,000	2.00	4,000			

Formula for Magnetic Reluctance.—Magnetic reluctance is expressed in the following equation:

$$R = \frac{l}{s \times \mu}.$$

Where R = Reluctance in Oersteds.
l = Length of magnetic circuit in centimeters.
μ = Permeability.
s = Cross-section in square centimeters.

From the foregoing it is evident that the reluctance of a magnetic circuit increases directly with the length like the resistance of an electric circuit. The reluctance also decreases as the product of the permeability and the cross-section. That is, the greater the cross-section and the higher the permeability, the less will be the total reluctance. This is precisely the way in which the resistance of an electric circuit varies, for the greater the length of a wire the greater its resistance, and the greater the cross-section and the better the conductivity the less will be its resistance.

Professor Henry Rowland, of Johns Hopkins University, discovered a law for magnetic circuits which very closely follows the law for electrical circuits. Ohm's Law for electrical circuits is:

$$\text{Current} = \frac{\text{Electro-motive-force}}{\text{Resistance}}. \quad I = \frac{E}{R}.$$

Rowland's law for magnetic circuits is:

$$\text{Magnetic Flux} = \frac{\text{Magneto-motive-force}}{\text{Magnetic reluctance}}. \quad \Phi = \frac{F}{R}.$$

The electric circuit is illustrated in Fig. 135. The magnetic circuit is illustrated in Fig. 136.

Formula for Total Magnetic Flux.—The detailed formula for the total flux is as follows:

$$\Phi = \frac{4\pi \times \frac{I}{10} N}{\frac{l}{\mu \times s}} = \frac{F}{R}. \qquad (1)$$

The 4π factor is used to account for the number of lines of force which must pass through a magnet or a solenoid in order to produce an intensity of one magnetic line of force per square centimeter at a distance of one centimeter away from the pole.

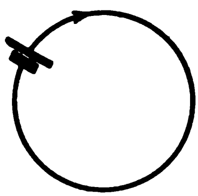


FIG. 135.

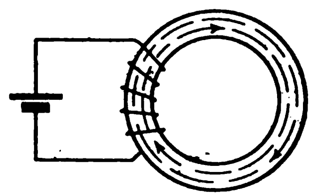


FIG. 136.

The constant, 10, is introduced to reduce the amperes to absolute units. As one ampere is $\frac{1}{10}$ of an absolute unit, the current in amperes must be divided by 10, for the total magnetic flux in lines of force is expressed in absolute magnetic units.

In an electric circuit, 1 Ampere $= \frac{1 \text{ Volt}}{1 \text{ Ohm}}$.

In a magnetic circuit, 1 Maxwell $= \frac{1 \text{ Gilbert}}{1 \text{ Oersted}}$.

Reducing equation 1 it reaches the following simplified form:

$$\Phi = \frac{12.57 \times \frac{I}{10} \times N}{\frac{l}{\mu \times s}};$$

$$\Phi = \frac{1.257 \times IN}{\frac{l}{\mu \times s}}.$$

Φ = Total magnetic flux in Maxwells.
IN = Ampere-turns.
l = Length of magnetic circuit in centimeters.
s = Cross-sectional area of magnetic circuit in square centimeters.
μ = Permeability.
1.257 = Constant for centimeter measurements.

The magnetizing force is proportional to the ampere-turns. The "1.257" constant is a rectifying factor to reconcile the lines within a coil with the unit intensity of field produced by that coil and the magnetic lines of force in absolute units with the current in amperes, which is in practical units.

Formula for Ampere-Turns.—It is not often that the unknown quantity in a magnetic circuit is the magnetic flux. It is usually required to know the ampere-turns necessary to produce a given total flux. The formula for centimeter measurements may therefore be transposed as follows:

$$IN = \frac{\Phi \times \frac{l}{\mu \times s}}{1.257}.$$

As there are 2.54 centimeters in one inch, the above formula may be used where the length of the magnetic circuit is given in inches and the cross-sectional area in square inches by changing the constant to 1.257 times 2.54 equals 3.192.

Thus:

$$IN = \frac{\Phi \times \frac{l}{\mu \times s}}{3.192}.$$

Where:

IN = Ampere-turns.
Φ = Total magnetic flux in Maxwells.
l = Length of magnetic circuit in inches.
s = Cross-sectional area of magnetic circuit in square inches.
μ = Permeability.
3.192 = Constant for inch measurements.

It is important to distinguish between the intensity of magnetizing force, H, and the total magneto-motive-force, F:

$$H = \frac{1.257\,IN}{l}.$$

This is the intensity of the magnetizing force **per centimeter of length.** The **magneto-motive-force in Gilberts, F, for any coil is** $1.257IN$. This is the **total magnetizing force.**

Figure 137 illustrates the relation between H and F, and between B and Φ. Here H represents the intensity of the magnetizing force per centimeter of length, while F represents

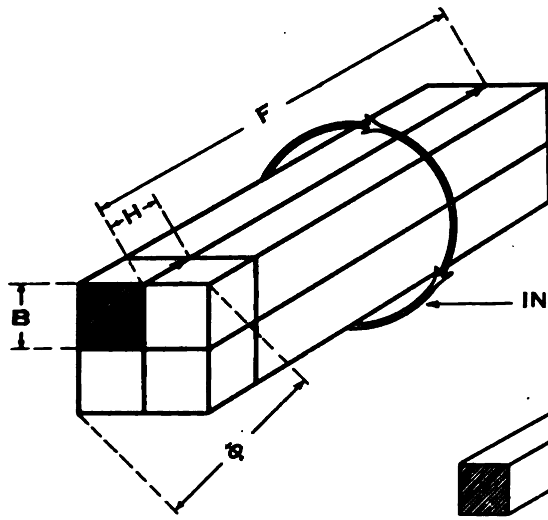


FIG. 137.

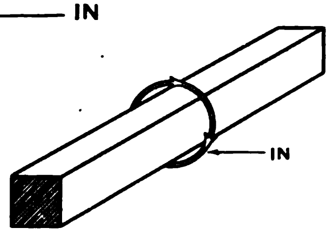


FIG. 138.

the total magneto-motive-force for the whole bar expressed in Gilberts. B represents the flux density in lines of force per square centimeter, expressed in Gausses, while Φ represents the total magnetic flux for the whole four square centimeters expressed in Maxwells. If the magnetic circuit is of uniform cross-section and permeability, as in an iron ring, then the equation

$$IN = \frac{\Phi \times \frac{l}{\mu \times s}}{1.257}.$$

may be reduced to a more simple form by dividing the cross-section, s, into the flux, Φ. This eliminates both of these quantities and gives

$$IN = \frac{B \times \frac{l}{\mu}}{1.257}.$$

It will now be observed that the required ampere-turns in a circuit do not depend upon the total flux, Φ, to be produced,

but only upon the **flux density,** B. Assume a bar of one square centimeter cross-section, Fig. 138, surrounded by one ampere-turn, and that a flux density of 10,000 lines per square centimeter is produced therein. If the iron bar in Fig. 137 is of the same quality and length, but possesses four square centimeters cross-section, then one ampere-turn surrounding this bar will produce 10,000 lines per square centimeter in each of the four square centimeters cross-section. In this case the total flux is 40 kilomaxwells, while in Fig. 138, the total flux is but 10 kilomaxwells. It takes the same number of ampere-turns in each case to produce these **totally different results** as far as **total flux** is concerned. The truth of this statement, however, is emphasized from the above formula, which states that the ampere-turns in any case are governed by the **flux density,** B, and **not** by the **total flux,** Φ, provided the magnetic circuit is of uniform cross-section, permeability and length in both cases.

If the magnetic circuit consists of a number of portions of different permeabilities and cross-sections, the total flux could not be divided by any cross-section to simplify the formula as above, but the separate reluctances would all have to be added and reduced to one total value. Then that reluctance must be multiplied by the total flux and divided by the constant, to obtain the ampere-turns, as shown at the bottom of page 171.

A graphic conception of a magnetic line of force may be obtained by a study of Fig. 139. Here suppose that a conductor A, one centimeter in length, is bent into an arc of a circle on a radius of one centimeter. The loops of force around the conductor will concentrate at the point B. If now a current of 10 amperes passes through this arc of conductor, there will be concentrated at the point B, the equivalent of one magnetic line of force. Thus one absolute unit of current (10 amperes), passing through one absolute unit of length of conductor (one centimeter), said conductor being curved on a radius of one absolute unit (one centimeter), will produce an intensity of field at the center of one absolute magnetic line of force (one Maxwell).

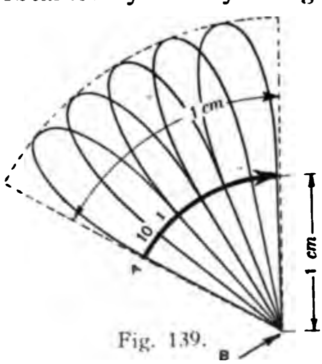


Fig. 139.

The practical application of the ampere turn formula will be seen from the following example: Suppose it is desired to produce a flux of 20,000 Maxwells, Φ, in an iron ring, Fig. 140, having a mean circumference of 150 centimeters and a cross-section of 4 square centimeters. Required the ampere turns. From the permeability table, on page 173, wrought iron at a flux density of 5,000 lines per square centimeter is found to have a permeability of 3,000.

$$IN = \frac{\Phi \frac{l}{\mu s}}{1.257} = \frac{20{,}000 \times \frac{150}{3000 \times 4}}{1.257} = 200.$$

These 200 ampere-turns may be composed of a coil of 200 convolutions, carrying 1 ampere, or a coil of 20 turns carrying 10 amperes, or any combination in which the product of the amperes and the turns equals 200.

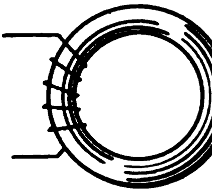


FIG. 140.

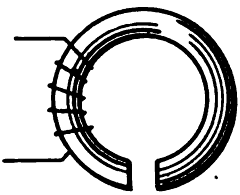


FIG. 141.

Now, assume an example in which it is desired to produce 65,000 Maxwells in a ring of 50 centimeters mean circumference and 5 square centimeters cross-section.

$$B = \frac{\Phi}{s} = \frac{65{,}000}{5} = 13{,}000 \text{ lines per square centimeter.}$$

From the permeability table, page 173, a value of 1,083 for wrought iron is obtained for this flux density. The required ampere-turns may now be calculated as before:

$$IN = \frac{65{,}000 \times \frac{50}{1083 \times 5}}{1.257} = 480 \text{ ampere-turns.}$$

Next, suppose that this iron ring is cut at the bottom and the poles pulled apart one centimeter, Fig. 141. The magnetic reluctance has now been increased by the addition of an air gap in series. The total ampere-turns now required will be expressed by the equation:

$$IN = \frac{\Phi \times \left(\frac{l}{\mu s} + \frac{l'}{\mu' s'} \ldots .\right)}{1.257}.$$

where l' = length of air gap
μ' = permeability of air gap
s' = cross-section of air gap

and the other letters have the same meaning as before.

The reluctances in series must be added as are electrical resistances in series. Their sum must then be multiplied by the flux and divided by the constant 1.257, to find the required ampere-turns. In the field circuits of generators it is not uncommon to have as many as five separate reluctances, all having different permeabilities, in series. Carrying out the above calculations gives the following result:

$$IN = \frac{65{,}000 \times \left(\frac{50}{1083 \times 5} + \frac{1'}{1' \times 5'}\right)}{1.257} = 10{,}900 \text{ ampere-turns.}$$

It will now be observed that the ampere-turns with the air gap are more than twenty times the number required without the air gap, to bring about the same total flux. Generators always involve an air gap in their magnetic circuits. From the above calculation it will be seen that the great bulk of the ampere-turns

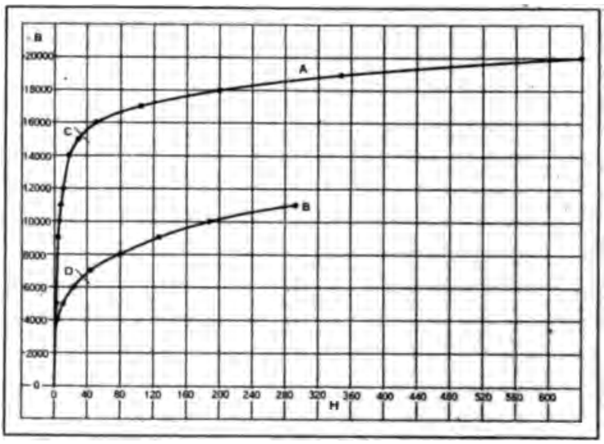


FIG. 142.—A, Permeability curve for wrought iron. B, Permeability curve for cast iron.

are required to force the flux across the air gap in a generator and only comparatively few are required to force the magnetism through the iron.

The permeability of wrought iron can be shown graphically by means of curves. These curves represent the ratio of mag-

netization, plotted as ordinates, to the magnetizing force, plotted as abscissas. Curve *A*, Fig. 142, represents wrought iron, while *B* represents cast iron. These curves are based upon the data in the following table:

Annealed wrought iron			Grey cast iron		
B	μ	H	B	μ	H
5,000	3,000	1.66	4,000	800	5
9,000	2,250	4	5,000	500	10
10,000	2,000	5	6,000	279	21.5
11,000	1,692	6.5	7,000	133	42
12,000	1,412	8.5	8,000	100	80
13,000	1,083	12	9,000	71	127
14,000	823	17	10,000	53	188
15,000	526	28.5	11,000	37	292
16,000	320	50			
17,000	161	105			
18,000	90	200			
19,000	54	350			
20,000	30	666			

Magnetizing force is developed by circulating a current in a coil. The resulting magnetization is ascertained by observing the result upon a sample of iron inserted within the coil. Instruments for this purpose are known as permeability meters, various forms of which have been devised.

Curve *A* exhibits the following qualities: With the application of a very moderate force, the resulting magnetization rises rapidly. After passing the point *C*, however, the application of greatly increased magnetizing force results in comparatively small increase in magnetization. The point *C* is called the knee of the curve, and it indicates the approach to saturation. After a flux density of 20,000 lines has been obtained it is evident that an indefinite increase in the magnetizing force will not result in any appreciable increase in magnetization.

Curve *B* shows that cast iron is incapable of developing anything like the flux density which may be produced in wrought iron. The curve does not rise as abruptly as with wrought iron and the location of the knee is less pronounced. At the point *D*, however, the curve shows that further increase in magnetizing force produces comparatively small increases in magnetization.

At about 10,000 lines per square centimeter, cast iron is practically saturated. These curves show graphically the quality of different kinds of iron for magnetic purposes. They give a better idea of permeability at a glance than can possibly be obtained by observing the table from which they are plotted. The ability of iron and steel to retain magnetism after the withdrawal of the magnetizing force has already been noted.

Residual Magnetism.—It will now be necessary to study some of the effects of residual magnetism. If a piece of iron is sub-

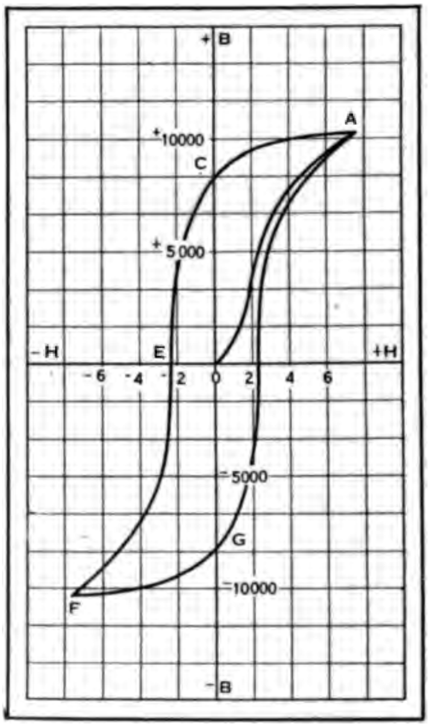


FIG. 143.—Hysteresis loop.

jected to an increasing magnetizing force and the magnetizing force is then decreased to zero, some residual magnetism remains. If the results are plotted in a curve it will exhibit the following peculiarities. On first increasing the magnetizing force, H, Fig. 143, from O, the resulting flux density increases from O to A. If, when the curve has risen to A, H is now decreased, the descending curve does not follow the ascending

curve owing to the retention of the magnetism. When H has been reduced to zero the magnetism falls to the point C, where it remains. The magnetic flux, O-C, represents the **retentivity** of the iron. This residual value depends upon the quality of the material and upon the degree to which B was first pushed. If, now, a reversing magnetizing force, $-H$, is applied by sending a current in the reverse direction through the magnetizing coil, it is found that it must be increased to a definite degree such as E, in order to demagnetize the iron and bring the magnetization curve down to O. The magnetizing force, O-E, necessary to bring it down to zero, is called the **coercive force.** If the reversed

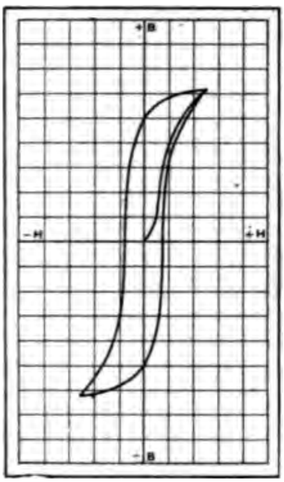


FIG. 144.—Hysteresis loop for wrought iron.

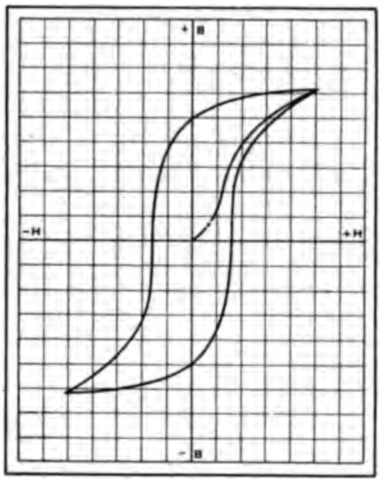


FIG. 145.—Hysteresis loop for hard steel.

magnetizing force is continued still further to $-H$, the curve descends from E to F, the iron now becoming magnetized with reversed polarity, reaches saturation in this direction. On diminishing the reversed magnetizing force to zero, the magnetization sticks again at G, showing a retentivity in the reverse direction equal to the original. If the magnetizing force is now reversed and applied to full value in the original direction, the magnetization curve will again fall to zero, and then ascend to A. When the magnetizing force has thus been carried through a cycle, the resulting magnetization also goes through a cycle.

Hysteresis.—It will be observed that there is always a lagging of the magnetization behind the application of the magnetizing

force. This lagging of magnetic results behind their cause is termed **hysteresis.** Fig. 144 represents an hysteresis loop for wrought iron and magnetic steel, while Fig. 145 represents the corresponding loop for hard steel. The area enclosed within these hysteresis loops is a measure of the energy required to supply the hysteresis loss in the two samples under test, re-

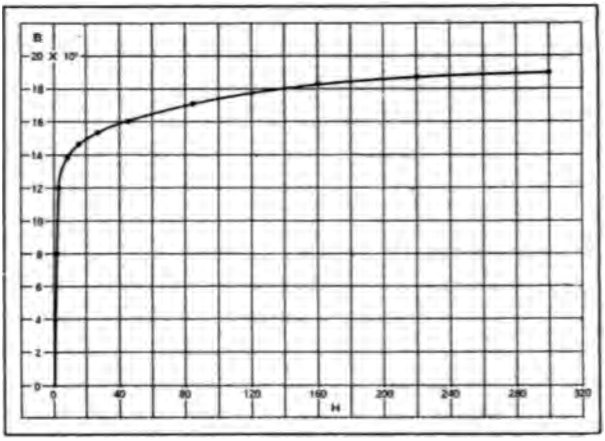


FIG. 146.—Permeability curve of high grade silicon steel.

spectively. Fig. 146 represents a permeability curve for silicon steel for electrical purposes, manufactured by a leading steel company. The high permeability is emphasized by the abruptness of rise, a high flux density being reached by the application of moderate magnetizing forces.

SECTION V CHAPTER II

ELECTROMAGNETISM

LAWS GOVERNING MAGNETIC CIRCUITS

1. Define a "maxwell."
2. Define a "gauss."
3. Define magnetic permeability.
4. What is the permeability of air?
5. If the application of 10 units of magnetizing force to a solenoid produces 10 lines of force per square centimeter in the core, of what is the core constructed?
6. If a better conducting core is placed in the above solenoid and the application of the same magnetizing force brings about the production of five kilogausses, what is the permeability of the new core?
7. What is meant by "H", the intensity of the magnetizing force? Give formula and tabulate meaning of each symbol.
8. What is meant by the total magneto-motive-force in a circuit? What is the unit?
9. What is meant by the magnetic reluctance of a circuit? What factors enter into it? What is the unit of reluctance?
10. Give the formula for the magnetic reluctance of a circuit. Tabulate the meaning of each symbol.
11. State in words, Ohm's Law for electrical circuits. State in words Rowland's Law for magnetic circuits.
12. Give the complete formula for the total magnetic flux produced in any magnetic circuit (centimeter measurements). Tabulate meaning of each symbol used.
13. State the formula for the ampere-turns required to produce a given flux, in a magnetic circuit (centimeter measurements).
14. State the formula for the ampere-turns required to produce a given magnetic flux in a magnetic circuit (inch measurements). Why the change in constant?
15. Distinguish between intensity of the magnetizing force in a circuit and the total magneto-motive-force in gilberts.
16. How many more ampere-turns would be required to produce a given flux density in an iron core of twelve square inches cross-section than would be required in a bar of six square inches cross-section?
17. Required: The ampere turns to produce a total flux of 100,000 lines of force in a circuit 75 centimeters in length with a cross-section of ten square centimeters; permeability 2,000.
18. The reluctance of the magnetic circuit of a certain electro-magnet is 0.5 oersteds. What is the total magneto-motive-force in gilberts which will be required to produce a flux of 100 kilo-maxwells?
19. If the magnetizing coil in the above problem contains 10,000 turns of wire, how many amperes will be required?

20. The total magnetic flux in a given electro-magnet is 300,000 lines. A coil of 500 turns carrying 1.5 amperes is wound thereon. What is the reluctance of the magnetic circuit in oersteds?

21. An electro-magnet has a coil of 1,200 turns. The reluctance of the magnetic circuit is 0.007 oersteds. How many amperes will be required in the coil to produce a flux of 500 kilo-maxwells?

22. A bar of iron is 200 centimeters long and has a cross-sectional area of 10 square centimeters. The permeability is 2,000. What is its reluctance?

23. A magnetic circuit consists of the following parts: The first part L = 30 centimeters; $S = 4 \times 3$ centimeters; the material is cast iron and the permeability, 200. The second part, L = 25 centimeters; $S = 2 \times 3$ centimeters. The material is annealed steel and the permeability is 2,000. The third part consists of an air gap 3 centimeters long and 3×2 centimeters cross-section. Find the reluctance of the entire circuit.

24. What will be the total number of ampere-turns required to produce 200,000 magnetic lines in the above circuit?

25. A wrought iron magnetic circuit is 250 centimeters long. The total flux is 1,000,000 magnetic lines. The flux density is 5,000 gausses.

(*a*) What is the cross-section of the path?
(*b*) What is the permeability for this density?
(*c*) How many ampere-turns will be required?
(*d*) What is the total reluctance of the circuit in oersteds?

26. A magneto-motive-force of 500 gilberts is necessary to produce the requisite flux in an iron rod. If the magnetizing coil contains 300 turns of wire with a total resistance of 75 ohms what e.m.f. must be applied to the coil?

27. A magnetic circuit is made up of 150 centimeters of wrought iron of 30 square centimeters cross-section; 100 centimeters of cast iron of 50 square centimeters cross-section; 1.5 centimeters of air of 40 square centimeters cross-section. How many amperes must circulate through a coil of 10,000 turns in order to produce a flux of 500,000 magnetic lines in this circuit?

28. A magnetic circuit consists of the following parts: 120 centimeters of wrought iron in which B = 13,000 gausses; 100 centimeters of cast iron in which B = 5,000 gausses; 0.5 centimeters of air in which B = 6,000 gausses. Required: The ampere turns necessary to maintain these flux densities.

29. A wrought iron ring has a cross-sectional area of 30 square centimeters. If the mean circumference is 160 centimeters, how many ampere-turns will be required to produce a flux of 30 kilo-maxwells?

ELECTRO-MAGNETISM

LIFTING POWER OF MAGNETS

The formula for the lifting power of a magnet is as follows:

$$l.p.d. = \frac{B^2a}{8\pi}.$$

Where $l.p.d.$ = lifting power in dynes
B = lines of force per square centimeter
a = area in square centimeters of both poles employed in lifting
8π = constant.

$$l.p.lbs. = \frac{B^2a}{11,183,500}.$$

Where $l.p.lbs.$ = lifting power in pounds.

11,183,500 = 8 × 3.1416 × 981 (dynes in a gram) × 453.6 (grams in a pound).

11,183,500 × 6.45 (square centimeters in one square inch) equals 72,134,000. The lifting power of a magnet in pounds for inch measurements then becomes:

$$l.p.lbs. = \frac{B^2a}{72,134,000}.$$

Where $l.p.lbs$ = lifting power in pounds.
B = number of lines of force per square inch.
a = area of both poles in square inches.

The unknown quantity in the design of lifting magnets is usually the number of lines of force per square inch required to bring about a certain lifting power. Transposing the above formula and reducing the expression to its simplest terms:

$$B = \sqrt{\frac{lbs. \times 72,134,000}{a}}.$$

$$B = \sqrt{72,134,000} \times \sqrt{\frac{lbs.}{a}}.$$

$$B = 8493 \times \sqrt{\frac{lbs.}{a}}.$$

By the foregoing formula the required flux density may be obtained to produce any desired lifting power. Inserting this value in the ampere-turn formula on page 168, the required ampere-turns to produce this flux density may be calculated.

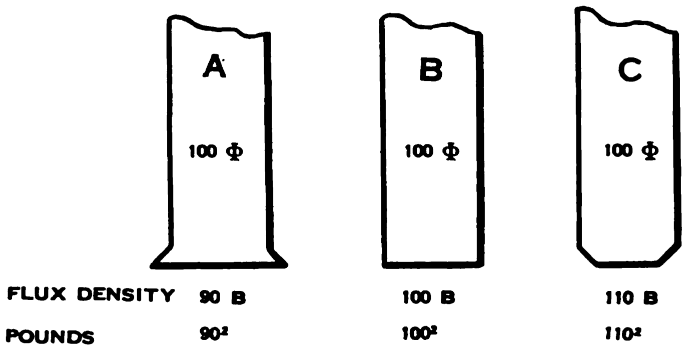


FIG. 147.

One curious result of the law governing the lifting power of a magnet is that reducing the polar area will very often result in an increased lifting power. Consider three magnets, *A*, *B* and *C*, Fig. 147. Assume that these magnets have equal cross-sections and carry 100 maxwells each. The strength of these

FIG. 148.—Iron clad electromagnet.

magnets, that is, the amount of free magnetism at their poles, will be the same in all cases. Next, suppose that the pole of *A* is expanded. The flux density falls to 90 lines per square centimeter at the pole. The pole of *B*, which is not expanded,

will have a flux density of 100 lines per square centimeter, while the pole of C, which is chamfered, will have a flux density of 110 lines per square centimeter. The lifting power of A will be less, of B, more, and of C, most. This is because the lifting power is proportional to the square of the flux density and not to the simple flux density. If it was proportional to the simple density, then when the cross-section C was reduced, the increased density would just make up for the reduced section, and the lifting power would be the same as in B, but as the lifting power varies as the square of the flux density, there is a gain due to the increased density which exceeds the loss due to diminished polar area, and

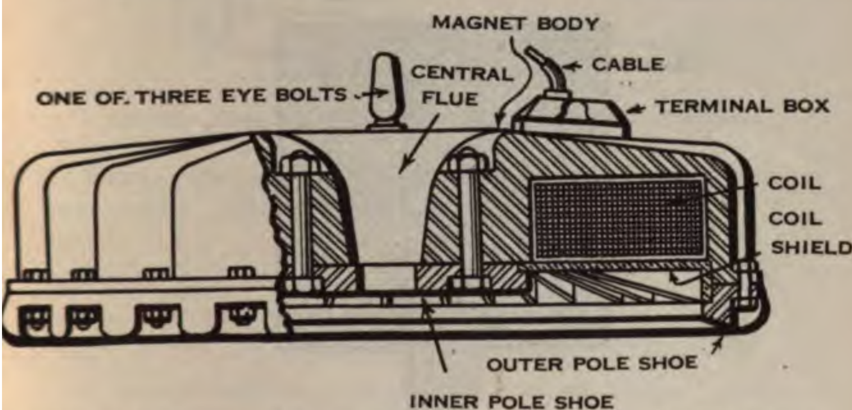


FIG. 149.—Commercial form of iron clad electro-magnet for lifting large weights by adhesion.

the net lifting power actually rises. This action could not be continued indefinitely for a point would be eventually reached where the pole of C would become saturated. The lesson to be learned, however, is that electro-magnets for lifting purposes should be worked at the highest practical flux density. This is about 110,000 lines per square inch.

Electro-magnets may be classed under three heads:

First, lifting magnets for lifting weights by adhesion. These are extensively used in steel mills. One of the common forms is an iron-clad structure containing a single coil, as shown in Fig. 148. The maximum lifting power of an electro-magnet is approximately 200 pounds per square inch. These magnets are built with a diameter of 40 or 50 inches and a capacity for lifting

several tons. The energizing coil is wound to operate on 110 or 220 volts direct current. These magnets are very satisfactory for quickly handling boiler plate and irregularly shaped pieces of steel as well as ingots too hot to touch. A detailed view showing the construction of a magnet of this type designed by the Cutler-Hammer Mfg. Co. is given in Fig. 149. In order that lifting magnets shall be economical in design, the magnetic circuit should be as short as possible, the cross-section of the path for the flux should be relatively large and the polar area of contact should be relatively small in order that the flux density may be high.

Second, magnets for producing mechanical motion. A

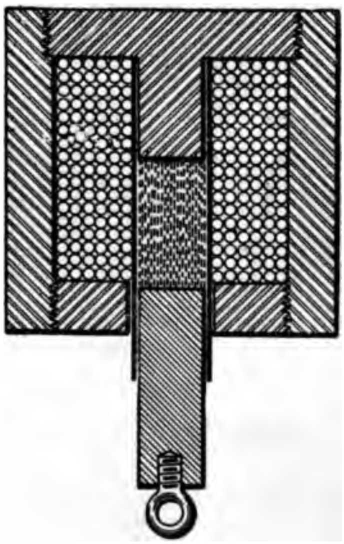


FIG. 150.—"Stopped" solenoid for producing long range of motion.

magnet for this type of work called a stopped solenoid, is shown in Fig. 150. The iron plunger moves in a brass tube on which the coil is wound. The magnetic circuit is complete save for a gap in the center of the coil. In accordance with Maxwell's rule the plunger tries to fill this gap in order to make the magnetic flux within the coil a maximum. The range through which mechanical motion can be produced, however, is quite limited, for no magnetic circuits having a range of motion of more than two or three inches are practical. Fig. 151 illustrates a magnet in which a longer range can be obtained by extending a lever from

the armature, *A*, to produce a magnified movement without increasing the length of the air gap. Self-winding electric clocks sometimes employ magnets of this type.

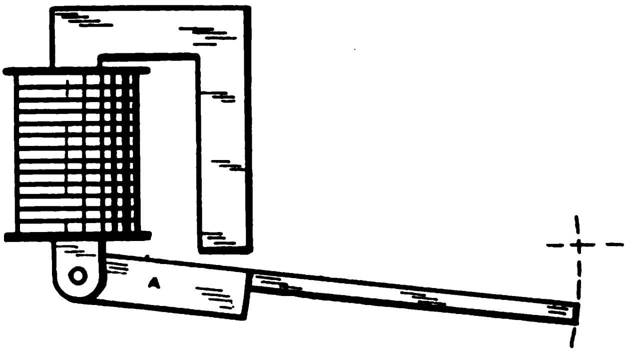


FIG. 151.—Long-range magnet, magnifying movement of armatures.

Third.—Magnets for producing fields of force, as in generators and motors. These are called **field magnets.**

SECTION V CHAPTER III

ELECTROMAGNETISM

LIFTING POWER OF MAGNETS

1. The flux density in a lifting magnet is 110,000 lines per square inch. What is the lifting power in pounds per square inch?
2. The lifting power of a certain magnet is 1,000 pounds. The area of both poles with which it lifts is six square inches. What is the total flux?
3. The flux density of a certain magnet is 100,000 lines per square inch. The area of both poles is four square inches. What is its total lifting power?
4. The area of both poles of a lifting magnet is eight square inches total. It lifts 400 pounds. If the area of the poles could be reduced to one-half without altering the total flux, what would the magnet lift?
5. What is the practical limit to the lifting power of a magnet in pounds per square inch?
6. What is the practical limit for the flux density in a lifting magnet?
7. Sketch a suitable design for a magnet capable of producing mechanical motions over a considerable range. Point out the advantages and disadvantages of this design.
8. Sketch a magnet for lifting weights by adhesion. What points should be observed in order that the magnet shall be most efficient?

INTERIOR WIRING

ELECTRIC BELLS, ANNUNCIATORS AND CLOCKS

A simple electric vibrating bell is shown in Fig. 152. The current circulates around the coils, as shown in Fig. 153. This produces the polarity indicated. Entering by the binding post *A*, Fig. 152, and passing through the coils, the current reaches the contact screw *C*, thence passes via a spring *S*, and the pivoted armature *D*, to the binding post *B*. The cores of the magnets and the armature being of soft iron, attraction ensues and the armature moves toward the pole pieces in an effort to shorten the air gap and increase the magnetic flux. Gaining momentum as it moves, the clapper *E* strikes the bell a sharp blow. At the same time the spring *S* breaks the circuit from the contact *C* and the current is interrupted. The iron being soft, immediately loses its magnetism, the armature is no longer attracted, and the spring *F* throws the contact piece *S* back against the screw *C*. As the spring *S* yields, the clapper *E* is thrown a considerable distance away from the bell. The circuit being completed, the magnets will again be energized and the operation is repeated. These magnets are usually wound with a resistance of about 1½ ohms and a bell 2½ inches or 3 inches in diameter is employed. The armature is frequently copper plated to prevent its sticking to the pole pieces due to residual magnetism. The contact point of the screw *C* and the spot where the screw touches on *S* are generally made of German silver or nickel in the cheaper grades of bells, or of platinum in the best types. This is to prevent corrosion of the con-

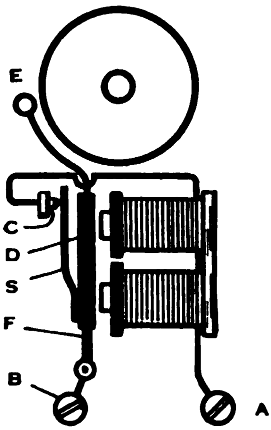


FIG. 152.—Ordinary vibrating electric bell.

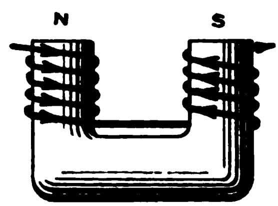


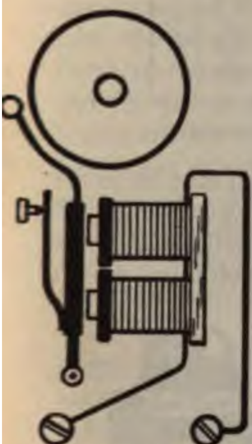
FIG. 153.

tacts due to the heat of the spark generated when the circuit is interrupted.

When it is desired to have a single stroke bell upon which signals may be tapped off, the make-and-break *C* of the vibrating bell is omitted. Current is then led through the binding posts directly to the magnetizing coils as in Fig. 154.

Fig. 155 shows the appearance of a powerful single stroke bell built on this principle.

In fire engine houses large electro-mechanical gongs are usually



IG. 154.—Single stroke electric bell.

FIG. 155.—Powerful single stroke electric bell.

FIG. 156.—Electro-magnetic gong for fire engine houses.

employed, Fig. 156. These contain a powerful clock spring or weight to actuate a train of gears connecting with a hammer. The gear train is controlled by an escapement which in turn is actuated by an electro-magnet. A number of bells may be operated in series from one central fire control station. When the circuit is closed the escapement is partially released. When the circuit is opened it is fully released and the hammer, actuated by the spring or weight, strikes the bell a powerful blow. These bells are thus mechanically operated but electrically controlled.

Annunciators

Where a number of calls are to be received at one central point from different stations, annunciators are employed. The diagram of connections for an annunciator used in hotels is shown

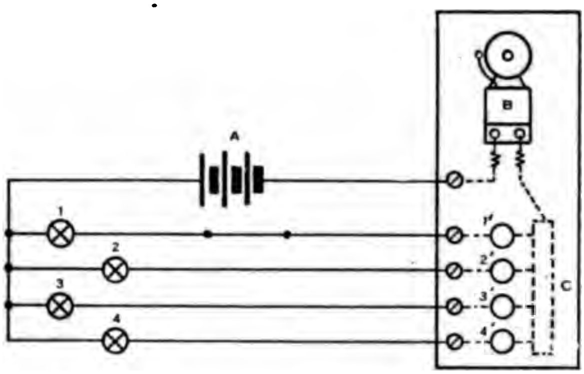


FIG. 157.—Electrical circuits for simple annunciator.

in Fig. 157. Stations 1, 2, 3 and 4 represent push buttons in the various rooms while 1′, 2′, 3′ and 4′ represent electro-magnetic coils in the annunciator, actuating some form of indicating device when current passes. No matter from what point the circuit

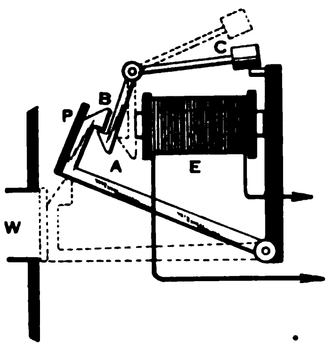


FIG. 158.—Principle of electro-magnetic drop for annunciators.

FIG. 159. — Annunciator employing drop shown in Fig. 158.

is closed, all current concentrates at a common point, C, and passes through the bell B and thence returns to the battery A. If the button 3 is pushed, current passes by the following route: A 3-3′-C-B-A.

Various forms of annunciator drops have been employed. One type contains an electro-magnet, *E*, Fig. 158, through which the current passes. The armature *A* is attracted and the latch *B* is released. A plate *P*, carrying the number of the room from which the call comes, then falls by gravity and exposes this number in the window, *W*, on the face of the annunciator. The counter-weight *C* insures the retaining of the number in a concealed position when the drop is reset. Fig. 159 represents the general appearance of a modern annunciator of this type.

Another form of annunciator very widely used for many years employs simply an electro-magnet with a slightly hardened iron core, Fig. 160. The pole, *P*, projects through the zinc face of the annunciator. Fastened on the face is a soft iron needle, *N*, standing about 3/8 of an inch from the projecting pole piece, *P*. When a current passes through the coil, the soft iron needle is attracted and moves over against the pole piece where it adheres through residual magnetism. A slight jar applied to the point *B* from a button in the bottom of the annunciator is sufficient to restore the needle to its original position. This is a simple and reliable system and hence is widely used.

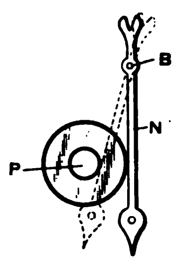


FIG. 160.

Electric Clocks

Electric clocks date back to the suggestion of Alexander Bain, an Englishman, who, in 1837, proposed that a number of clocks might be operated from one unit by electrical means. It was not, however, until 1899 that any practical electric clocks were devised. Now various forms are manufactured.

These might be divided into three classes:

Class 1. Master clocks.

(A) This involves the use of a master clock to operate a secondary circuit. Every clock in the secondary circuit contains only an electro-magnet, ratchet and pawl, with a short clock train, as shown in Fig. 161. Here current from the battery *B* controlled by the contact in the master clock, *A*, energizes an electro-magnet *E*. The armature of this mag-

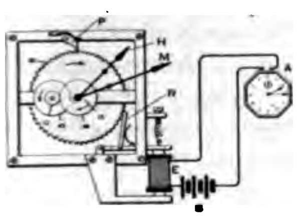


FIG. 161. — Mechanism of secondary electric clock.

net in descending, pulls down the ratchet *R* and moves a toothed wheel, containing 60 teeth, forward one step. The pawl *P* insures the locking of this wheel positively in position every time the wheel moves forward. The minute hand *M*, is attached to this wheel. Through suitable gear ratios the hour hand, *H*, moves forward the proper distance. A large number of these secondary clocks may thus be operated in series.

(B) A master clock may be employed to set other spring or weight operated clocks at 12 o'clock daily. By having a self-contained secondary clock with a reasonable degree of accuracy it is sufficient to send an impulse once in 12 or 24 hours, usually at exactly 12 o'clock, which will actuate an arrangement like a pair of pincers, which grasps the hour hand and the minute hand and lines them up positively.

Class Two.—This includes all forms of self-winding electric clocks which are operated by a spring or weight and are wound by an electro-magnet or a motor at definite intervals. When the clock has run down a certain amount an electric circuit is automatically closed which causes a motor to wind it up. The best clocks of this type use a mainspring which is wound by 50 or 60 impulses through an electro-magnet actuating an armature which in turn operates a ratchet, winding the spring. These impulses at the start are applied by a push button operated by hand. Thereafter an electrical circuit is automatically closed by a contact attached to the second hand, which causes the electro-magnet to wind the mainspring one notch each minute. Three cells of wet or dry LeClanche battery will generally operate a clock of this type for one year without attention.

Class Three.—This class represents the purely electric clock. This clock has no springs or weights, but an electro-magnet is employed to give the pendulum a push on each swing. Well-designed clocks of this type have an electro-magnet which in attracting its armature raises a weight. Upon the interruption of the circuit this weight falls and in so doing gives the pendulum the required impulse. If the movement of the armature directly actuated the pendulum the impulse would grow more feeble as the battery grew weaker. By having the magnet raise the weight, however, and then allowing it in its fall to push the pendulum, the actuating impulse is precisely the same until the battery fails to operate the magnet entirely. One cell of dry battery will run a clock of this sort for one year.

SECTION VI CHAPTER I

INTERIOR WIRING

ELECTRIC BELLS, ANNUNCIATORS AND CLOCKS

1. How does a single stroke bell differ from a vibrating bell?
2. What are two types of annunciators? Draw the circuits of a simple annunciator.
3. Draw the internal connections of an ordinary vibrating bell.

INTERIOR WIRING

BELL CIRCUITS AND BURGLAR ALARMS

Fig. 162 shows an elementary circuit for operating bells. Here the button *A* is connected across two wires, *C* and *D*. When the circuit is closed, current from *E* passes through the bell *F* and back to the battery. A button *B* may be connected in parallel with *A* to operate the bell from another point. This diagram shows that any number of buttons may be connected in multiple between *C* and *D*, each operating the bell independently of the others.

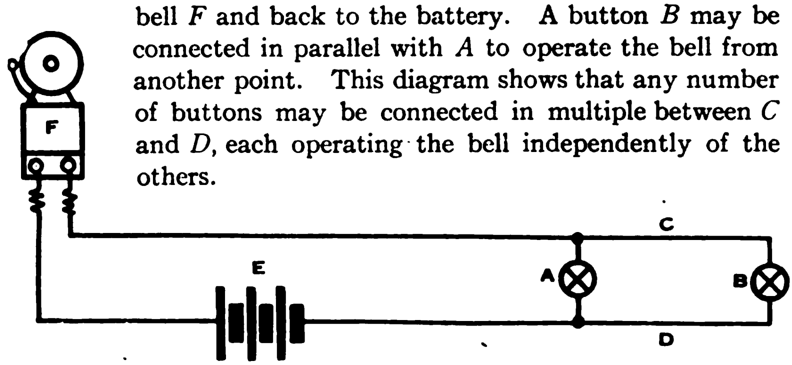


FIG. 162.—Single electric bell, operated from two or more push buttons.

Fig. 163 illustrates how any number of bells, each with its own push button, may be independently operated from a common

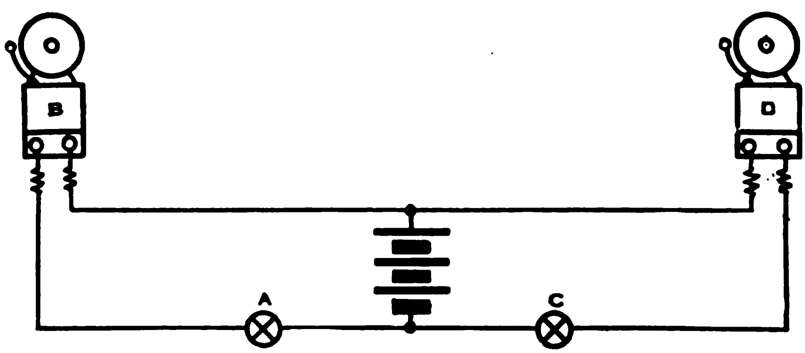


FIG. 163.—Two or more bells operated independently from a common battery.

battery. Thus, button *A* will ring bell *B*, and button *C* will ring bell *D*. Current from the battery flows through either bell under the direction of the corresponding push button.

Fig. 164 shows how button *C* and bell *D*, of Fig. 163, may be transposed in position so that signaling back and forth may be accomplished between two distant points.

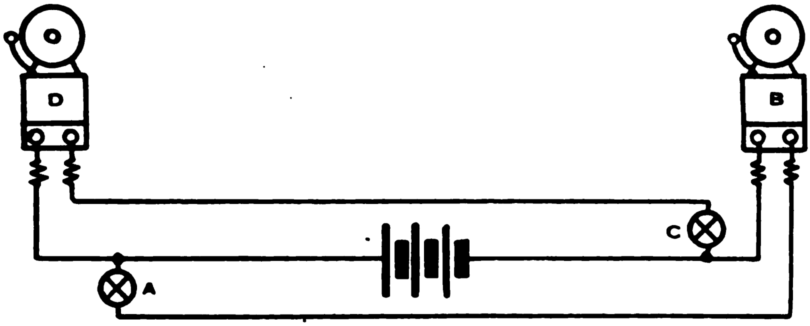


FIG. 164.—Two bells operated independently from opposite ends of a line with three-wire circuit and a common battery.

Factory Call

Fig. 165 illustrates a factory call system. Here any number of bells, *B-B-B*, are connected in parallel across wires *A-C*. Any number of buttons, *D-D-D*, are connected in parallel across wires *A-E*. It will be observed that the wire *C* is common to all the

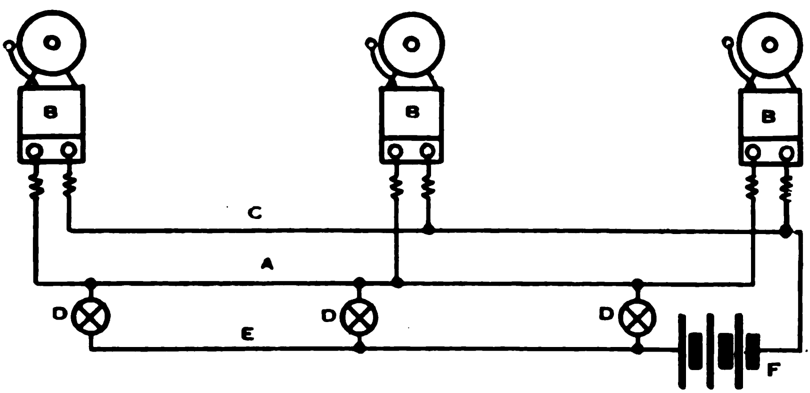


FIG. 165.—Factory call system for operating any number of bells in multiple from any number of push buttons in multiple.

bells. The wire *E* is common to all the buttons. Between the wire that is common to all the buttons and the wire that is common to all the bells, the battery *F* is looped in series. The wire *A* is common to all the bells and all the buttons. Any

number of buttons connected in multiple across A-E may be employed to operate any number of bells simultaneously.

Series Bells

Occasionally it is desired to operate bells in series. The ordinary vibrating bell cannot be satisfactorally operated if any considerable number are connected in series. The make-and-break device in the different bells interrupts the circuit at different intervals and the bells vibrate irregularly. To insure a smooth operation of bells in series it is necessary to employ one only with the usual make-and-break. This is called the **master bell.**

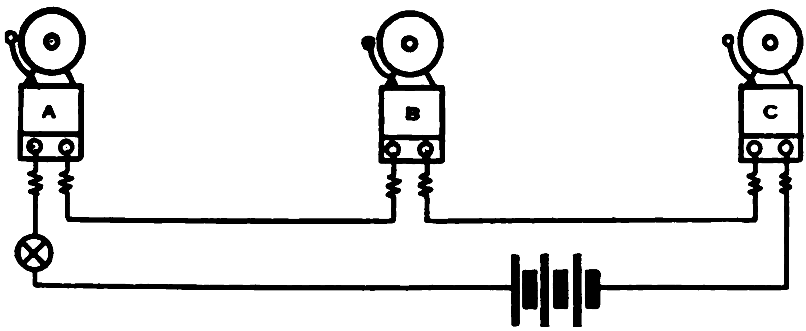


FIG. 166.—Electric bells operated in series with a master bell to control the entire series.

It interrupts the circuit for the entire series. All of the other bells have their make-and-break contacts short circuited and are therefore in effect, single stroke bells. Fig. 166 shows the arrangement where A is the master bell and B and C single stroke bells. If any considerable number are operated in series trouble will be experienced in sparking at the master bell's contact points. This may sometimes be partially cured by placing either a condenser or a high resistance in shunt with the master bell's contacts.

Relay Control

Where a considerable number of bells of large size are to be simultaneously operated at widely separated points, neither the factory call system, Fig. 165, nor the series arrangement, Fig. 166, are suitable. Under these conditions it is best to have a control circuit consisting of a button B, Fig. 167, which admits current to a series of 20 ohm relays, R-R-R, one of which is located close

to each bell to be rung. This relay actuates a local circuit which includes a few cells of dry battery located close to the bell. The drop due to the resistance of a long line is thus avoided and

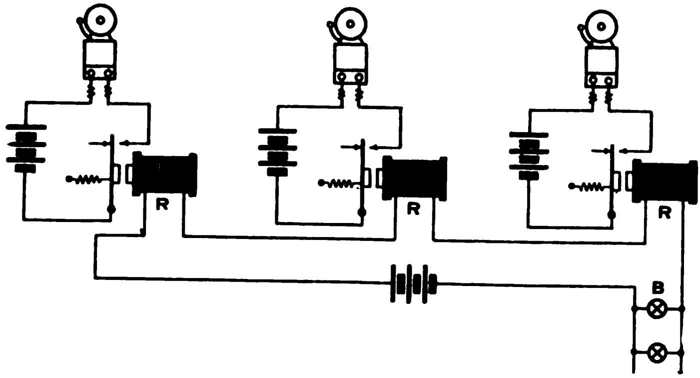


FIG. 167.—Operation of widely scattered bells through medium of relays with local battery situated at the bells.

all the bells ring with equal intensity no matter where they are placed.

Multiple Control

If, instead of using three wires to signal both ways as shown in Fig. 164, it is desired to accomplish this with two wires, it

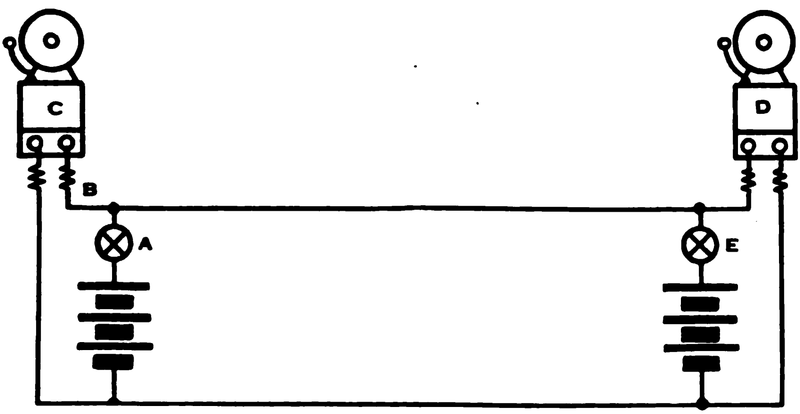


FIG. 168.—Two bells operated simultaneously by means of two batteries and only two wires.

may be done as shown in Fig. 168, provided the distance between the stations is not too great. The price that must be paid for the

saving of one wire is the addition of another battery. If the button A is pushed, current divides at the point B, part going through the bell C and part going through the bell, D. These two currents return to the battery from which they originate. Similarly, button E would operate bells C and D in multiple. If the two stations are several hundred feet apart, however, the bell C would get most of the current when A was pushed, the resistance of line causing D to get a very feeble current.

Return Call

A better arrangement is shown in Fig. 169. This is made possible by the use of double contact push buttons. This button has three terminals, the upper contact, U, the lower contact, D, and the strap or lever or heel, L. Both batteries are normally on

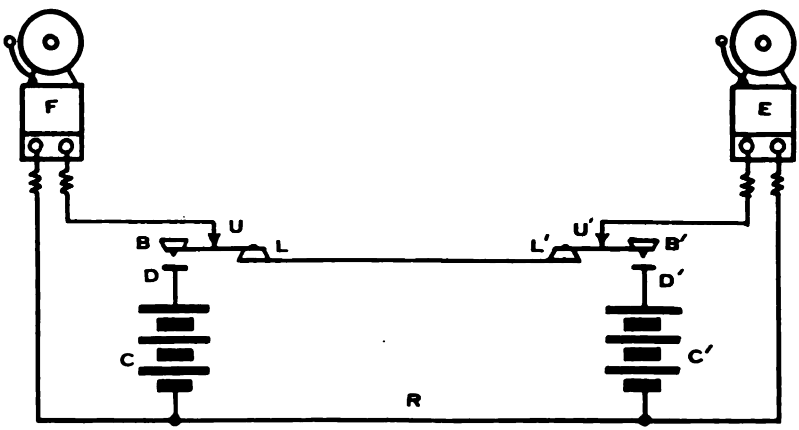


FIG. 169.—Return call push buttons for bells.

open circuit. If, now, the button B is depressed, the strap L breaks from the contact U and closes on the point D. The current from the battery C now passes via D and L, lever L' of the distant button, U', bell E and thence via the return wire R to the battery C. Bell E rings, but bell F does not. Releasing B, L breaks from D and springs back against U. The party at the distant station may now acknowledge the call by pressing B'. This closes the strap L' on D' and directs current from the battery C' via D'-L'-L-U, the bell F, and the return wire R to C'. Because of its application, this device is sometimes known as a **"return call button."**

Return Call Annunciators

The application of the return call to annunciators for hotel purposes permits the guest in a room to call the office and the office to acknowledge the signal by a return call on a bell located in the guest's room. The circuits for such a system are shown

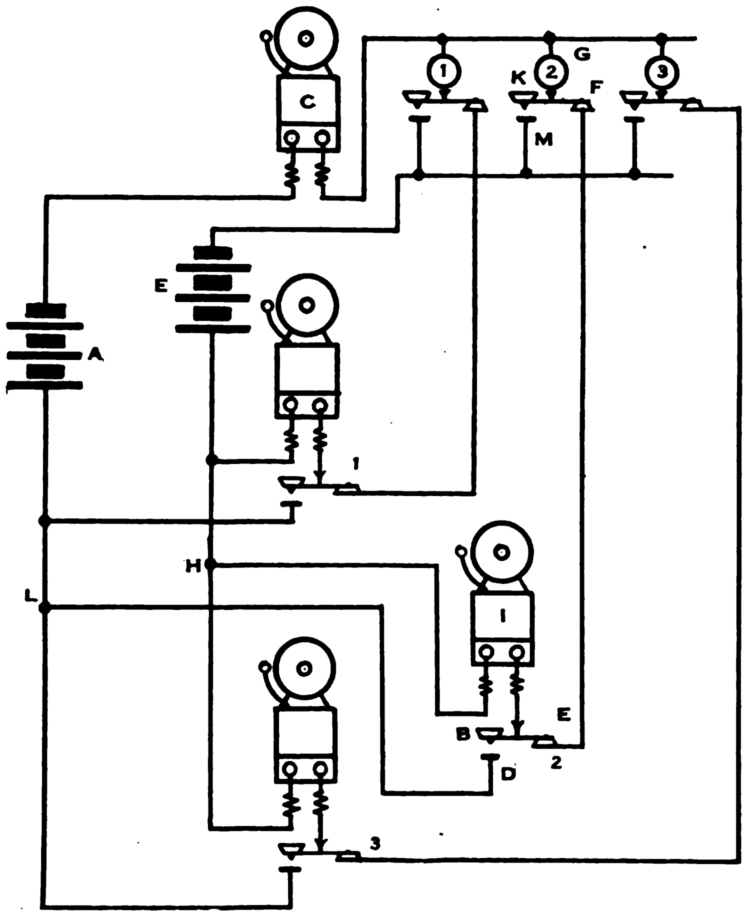


FIG. 170.—Return call annunciator wiring.

in Fig. 170. It is only necessary to add one common return wire to the simple annunciator system of Fig. 157. Thus, for a 100 room outfit the simple annunciator system in Fig. 157 would require 101 wires. There would be one individual wire leading

from each room to the annunciator and one common return wire passing through the battery from the bell to all of the rooms. In the return call annunciator system, Fig. 170, for a 100 room outfit there would be 102 wires. 100 would be individual lines leading from each room to the annunciator while there would be 2 common return wires leading from the annunciator to all the rooms. In each of these common return wires there is looped a battery. One battery is employed for outgoing signals from the annunciator and the other for incoming signals. Should the button *B* in room 2 be pushed, current from the battery *A*

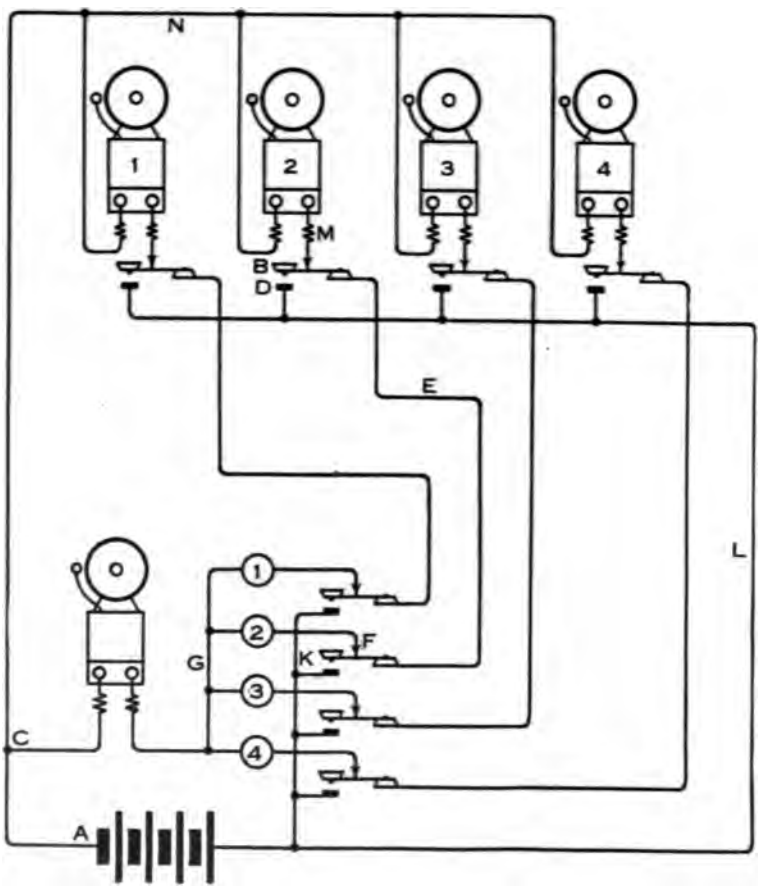


FIG. 170.—A.

takes the following circuit: A-L-D-B-E-F-G-C-A. To return the call the office depresses button K. Current now flows from the battery E via H-I-E-F-M-E, thus ringing bell I.

Fig. 170-A shows a one battery system accomplishing the same results as in Fig. 170. Should the button B in room 2 be pushed, current from battery A takes the following circuit: A-L-D-B-E-F-G-C-A. To return the call the office depresses button K. Current now flows from the battery A via K-E-M-2-N-C-A, thus ringing bell 2. While this system has some advantages, the system shown in Fig. 170 is considered more reliable. A return call system of this type can very readily have a telephone system added to it as will be explained in a later chapter.

Burglar Alarms

There are two systems of burglar alarm protection:

A, Open circuit systems.

B, Closed circuit systems.

Fig. 171 represents the simplest form of open circuit system. The feature of this system is the automatic drop or constant ringing attachment. This consists of an electro-magnet A,

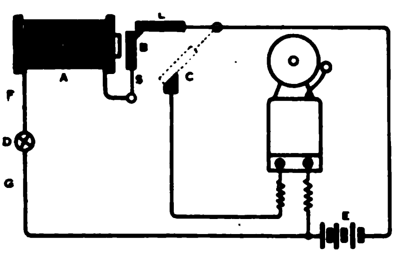


FIG. 171.

an armature, B, retained normally in the position shown by a spring, S, a lever, L, and a contact C. A push button which may be actuated by the opening of a window or door and known as a **window spring** or **door spring,** D, leads current from battery E, through the magnet A, thence via S-B and L back to E. The armature B is attracted and the lever L falls into the dotted position, completing the circuit with the contact C upon the bell. The bell now being on a local circuit will ring

continuously until the lever L is restored, even though the wires F and G connecting to the protected point, D, be cut away entirely. The actual arrangement of magnet and circuits in a modern automatic drop is shown in Fig. 172. If any one of the door or window springs, H, I, K, are closed, current from the battery E passes through L, contact point A, thence into the ground connection G and back through G', thence into the bell magnets, thence to F and through the contacts now closed, and to the

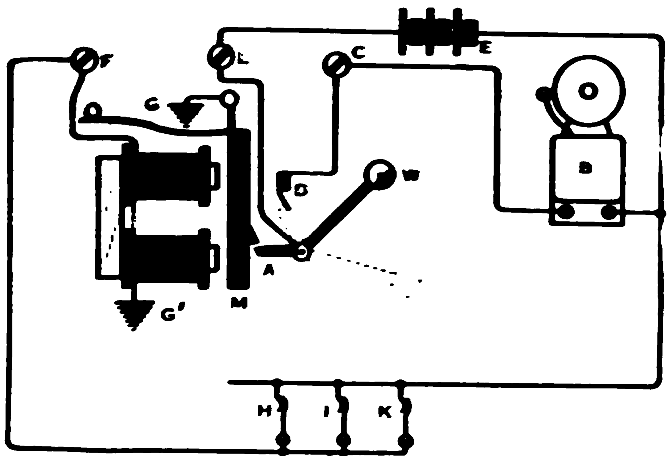


FIG. 172.—Standard wiring connections for automatic drop.

battery. The armature M is attracted. A is released and moves into the dotted position, closing contact D. Current from the battery then passes from E through L, D, C, bell B and thence to the battery. The bell will now ring continuously until the weight W is restored to its normal position.

Automatic Drop

The application of this device on an enlarged scale for the protection of a number of rooms is shown in Fig. 173. Here it will be observed that the closing of the circuit at any window or door spring, D, does not immediately operate the bell but current from the battery E passes into 1, thence through D-A-S-B-L and back to the battery. As soon as B is attracted and L falls, a local circuit is established, so that current passes from E through

H-C-L and back to the battery without going through the external circuit at all. Circuits *F-I* or *K* would similarly throw

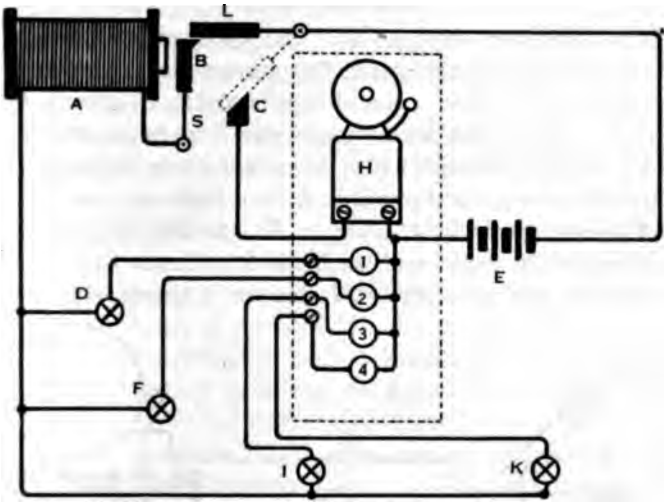


FIG. 173.—Automatic drop applied to ordinary annunciator.

the corresponding drop and indicate the source from which the call emanated.

Burglar Alarm Indicator

Fig. 174 shows a complete burglar alarm indicator system. It has, in addition to the ordinary annunciator, individual circuit cutouts, *C*, by means of which the front door of a house, for example, could be left disconnected while the rest of the house was protected, and a silent test switch, *St*, which permits short-circuiting the actuating coil *A* of the automatic drop temporarily before closing the battery switch *L* at night. This would cause a drop to fall in the annunciator without ringing the bell *H* in case any window or door had accidentally been left open. If a drop falls the switch *L* is then

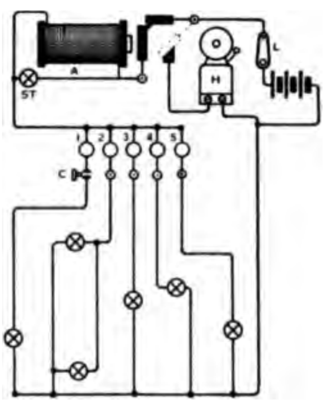


FIG. 174.—Open circuit burglar alarm indicator system.

opened and the window or door closed after which *L* may be closed.

Garage Alarm

Where wires are exposed and the prospective burglar may contemplate cutting the same, the garage-alarm shown in Fig. 175 is employed. Here a closed circuit spring, *S*, attached to the garage door, keeps the line normally closed when the door is shut. Current from three cells of blue stone gravity or Edison LeLande battery, *B*, passes via the switch *L*, line 1, closed contact *S*, line 2, and magnet coils *MM*, back to *B*. As this circuit does not pass through the make-and-break device, *C*, the armature *A* is attracted to the magnets *MM* and held there. If, however,

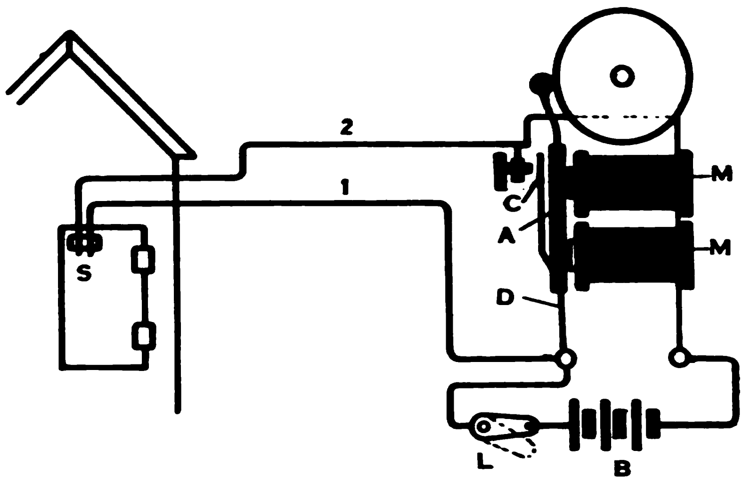


FIG. 175.

the wires 1 and 2 are cut, or the garage door opened, the circuit would be opened. The current now fails and the spring *D* throws the armature back and closes the contact at *C*. Current from the battery now passes via the circuit *L-D-A-C-M-M-B*. This connects the bell in the ordinary way for producing vibration and it rings as a vibrating bell until the switch *L* is opened. The switch *L* should be left open in the day time to prevent ringing of the bell and only closed at night when *S* is closed.

Balanced Relay System

For the protection of banks, a more elaborate system of burglar alarm shown in Fig. 176 is employed. This is the balanced relay system devised by G. B. Lehy, of Medford, Mass. It con-

sists of two electro-magnets, *A* and *B*, arranged to attract in opposite directions, an armature *C*. Current from a battery *D* divides at *E*, part going through *B* and a closed circuit spring *V*, in the vault, to be protected, whence it returns to the battery, the other part going through the electro-magnet *A*, auxiliary relay, *R*, whence it likewise returns to *D*. These circuits are made with practically the same resistance so that *A* and *B* attract equally the armature *C*. As it would be very difficult to balance this armature against opposing magnetic forces, adjustable spiral springs, *F* and *G*, are employed to perfect the balance. With the switch closed and the armature balanced, the contacts at *I* are open and the bell *K* does not ring. If, however, the vault is opened, the circuit via the wires *L-M*, through *B*, is interrupted, and *B* loses its attraction, causing the magnet *A* to pull the armature against the contact *I*. Current now flows from the battery *H* through *K-S* and *I*. *K* is a large powerful bell located in some protected position. If, on the other hand, the burglar knew enough to short-circuit the wires *L-M* before tampering with the vault, he would lower the

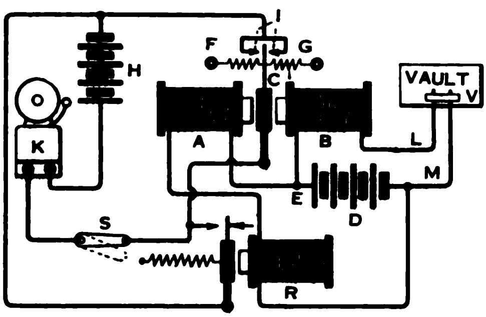


FIG. 176.—Closed circuit balanced relay burglar alarm system.

resistance of the circuit *D-E-B-L-M*. It will be noted that no jumper could be put across *L-M* without altering the resistance of this circuit. This will cause more current to flow through *D-E-B-L-M* than flows through *D-E-A-R*. This will now make *B* over power *A* and *C* will swing to the right, closing on *I* and completing the local circuit. Thus, if the resistance of the vault circuit is varied in any way, the relay will be unbalanced and the bell will ring. It will be noticed, however, that should battery *D*, which must be of the closed circuit type, run down, its effect on *A* and *B* would fall equally. *F* and *G* might now

maintain the armature in balance even though D was dead. Under these conditions the vault might be opened without sending in an alarm. To guard against this danger, relay R is inserted. As long as a proper current flows from the battery, D, the portion through A returns through R and keeps the armature forward. If, however, this current fails, R releases its armature and the spring pulls it back against a contact which closes the local circuit from the battery H through the bell K and gives the alarm. Because of the extreme delicacy of this system, it is apt to give false alarms, for it takes very little variation of the resistance of the circuit L-V-M to upset the balance.

Messenger Calls

Telegraph Messenger Call Systems, from a central station to subscribers' points, operate on two plans:

A, Open circuit systems, Fig. 177.

B, Closed circuit systems, Fig. 178.

The messenger call box contains a clock train with a main spring which is wound by pulling the lever on the box. An

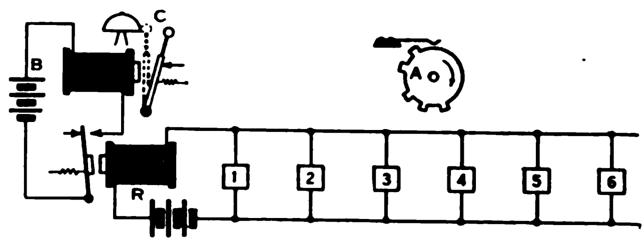


FIG. 177.—Open circuit messenger call system.

escapement, similar to that contained in an alarm clock, allows a contact making wheel, A, to revolve one revolution, every time the handle on the box is pulled. On the open circuit system this revolving wheel, A, closes the circuit any number of times required for the signal. In the closed circuit system the contact making wheel, B, maintains the circuit normally closed, the wheel opening the contact the required number of times. This is provided for by having the open circuit wheel carry projections while the closed circuit wheel has notches cut in it.

In the open circuit system the messenger call boxes are connected in parallel as shown at 1, 2, 3, 4, 5, 6, in Fig. 177. When box is pulled the circuit is automatically closed, the relay

R is energized, its armature is attracted and the battery *B* actuates a single stroke signal bell *C* and the clapper taps off the number of the box pulled.

In the closed circuit system the boxes 1, 2, 3, 4, 5, 6, Fig. 178, are connected in series. A closed circuit battery, *A*, maintains the current in the relay *R* and the armature is normally attracted. When a box is pulled this circuit is interrupted the required

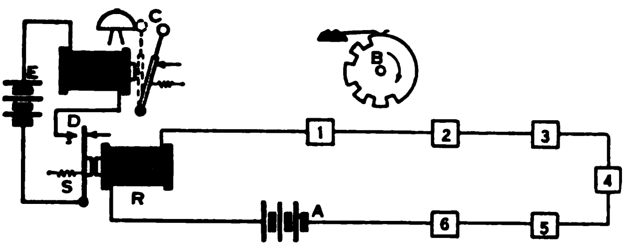


FIG. 178.—Closed circuit messenger call system.

number of times and the spring *S* pulls the armature back against the contact *D*, which closes the local battery *E* upon the bell *C*, and causes it to tap off the number corresponding to the box pulled.

Both systems permit of the use of 20 to 30 boxes upon one line, the actual number being governed by the amount of traffic to be handled.

SECTION VI CHAPTER II

INTERIOR WIRING

BELL CIRCUITS AND BURGLAR ALARMS

1. Draw a simple call bell using a two-point button and battery.
2. Is it practical to operate vibrating bells in series?
3. When several large gongs are to be operated in widely separated places, what method is usually employed?
4. How does a three-point push button differ from a two-point?
5. How many batteries are usually employed with a return call annunciator system? Is it possible to have a return call annunciator system with less than two batteries?
6. Draw the circuit for a return call annunciator system of four drops.
7. What two types of burglar systems are in general use? What are the advantages of each of these two types?
8. What is the automatic drop and for what is it used?
9. Can an annunciator be used in connection with a burglar alarm?
10. What are the advantages of the Lehy balanced relay system? Draw the circuits of this system. What two kinds of batteries should be used with this system? Where should each be used? What indication is used to how if the vault battery fails?

INTERIOR WIRING

INSIDE WIRING FOR LIGHTS

There are six different methods of installing wires in buildings for electric lighting and power:

1. Open work where wires are placed on porcelain knobs or in cleats exposed to view.
2. Wooden moulding, where the wires are concealed in wooden strips placed on the surface in finished buildings.
3. Metal moulding where wires are placed in a two-piece flat metal tube on the surface.
4. Concealed knob and tube work where the wires are strung on porcelain knobs or through porcelain tubes between floors and in partitions, before buildings are finished.
5. Conduit work, where wires are placed:
   A, In rigid iron pipes or conduits.
   B, In flexible metal conduits.
6. Concentric wiring where a single rubber insulated conductor is surrounded by a bare metallic tube, the latter being exposed to view and fastened with straps to the surface of walls and ceilings.

For open work in dry places a weatherproof wire is permitted and the wires must be strung 2½ inches apart and supported every 4½ feet of running length and at least ½ inch away from the surface wired over, while if dampness is present, a rubber insulated wire must be used.

In wooden moulding, rubber insulated wire only is permitted, the moulding being thoroughly painted inside and out with two coats of waterproof paint. It must consist of a backing and a capping. If it is to be mounted upon a masonry wall it must have a ⅞ inch wooden strip in addition, mounted behind it.

In metal moulding a twin conductor only is permitted. This consists of two wires each separately insulated with rubber and braided. The two are then covered with another braid, which binds them together, the whole being then saturated with a

waterproof compound. Metal moulding is not permitted in damp places and may only be used for branch lines.

Concealed knob and tube work is forbidden in some localities, though permitted in others. The wires are strung through porcelain tubes, placed in holes bored through joists between floors or in partitions. A minimum separation of 5 inches between wires is required and rubber insulated wires only are permitted.

A durable and satisfactory method of installing wires in buildings is to place them in rigid metal conduits. For this purpose a galvanized or enameled pipe, ½ inch in diameter (electrical trade size), is the smallest permitted. In this pipe a twin conductor is drawn after the pipe installation is complete. All bends in the pipe must be on long radius, so that the wires will not be injured in being drawn into position. Rubber insulated wire alone is permitted.

For "fishing wires" in inaccessible places in finished buildings a flexible metallic conduit containing rubber insulated conductors is approved. Various brands of this material are available. They are known as "Greenfield," "BX," etc. Occasionally this flexible conduit is installed without wires, provision being made for drawing the conductors into place afterward. It is usually employed, however, with the conductors built into the conduit as it is manufactured.

Although not generally approved at this time by the fire underwriters association, concentric wiring has been tried out with more or less success and has come into considerable use abroad. The simplicity and cheapness of this method commends itself for wiring inexpensive houses where the exposed conductor is not objectionable. It is permitted for branch lines only and no joints can be made in the circuit. The wire, No. 14, is rubber covered and then encased in a bare tube of copper or brass. The idea of insulating one wire with care and running the other bare is not new. Some ships in the United States Navy and many foreign vessels are provided with a single live wire, the steel hull of the vessel being used for the return circuit. A large office building in Providence was wired several years ago with one insulated conductor, the iron conduit forming the return for branch circuits. With the concentric system it will be practically impossible to receive an electric shock of any kind, for the ex-

posed return conductor will always be grounded and therefore at the potential of the earth.

Designation of Various Parts of Wiring Circuits

The various members of a complex wiring installation are designated as, **feeders, subfeeders, mains, branches** and **taps.**

A **feeder** is a stretch of wiring to which no connection is made except at its two ends. No lamps or other load are connected along its length. It is indicated at *A-B*, Fig. 179. A **subfeeder** is of the same class, but is distinguished from a feeder

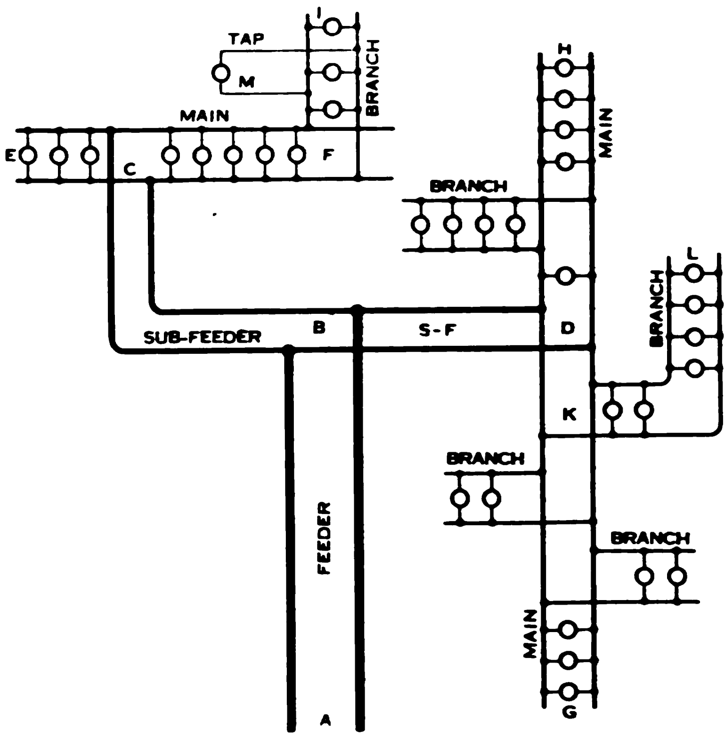


FIG. 179.—Designation of various portions of electrical circuits.

by being one of two or more connecting links between a feeder and a distributing system. Subfeeders are shown at *B-C* and *B-D*. A **main** is a stretch of wiring smaller than a sub-feeder, supplying one or more circuits with power. Electrical devices are not allowed to be connected across mains unless the fuse protecting the main will protect the device. A **branch** is a

line extending from a source or a main, carrying no more than 660 watts (in special cases 1,320 watts); lamps are connected across it. Branch lines should preferably be limited in length to 100 feet and the loss in potential in branch circuits should prefer-

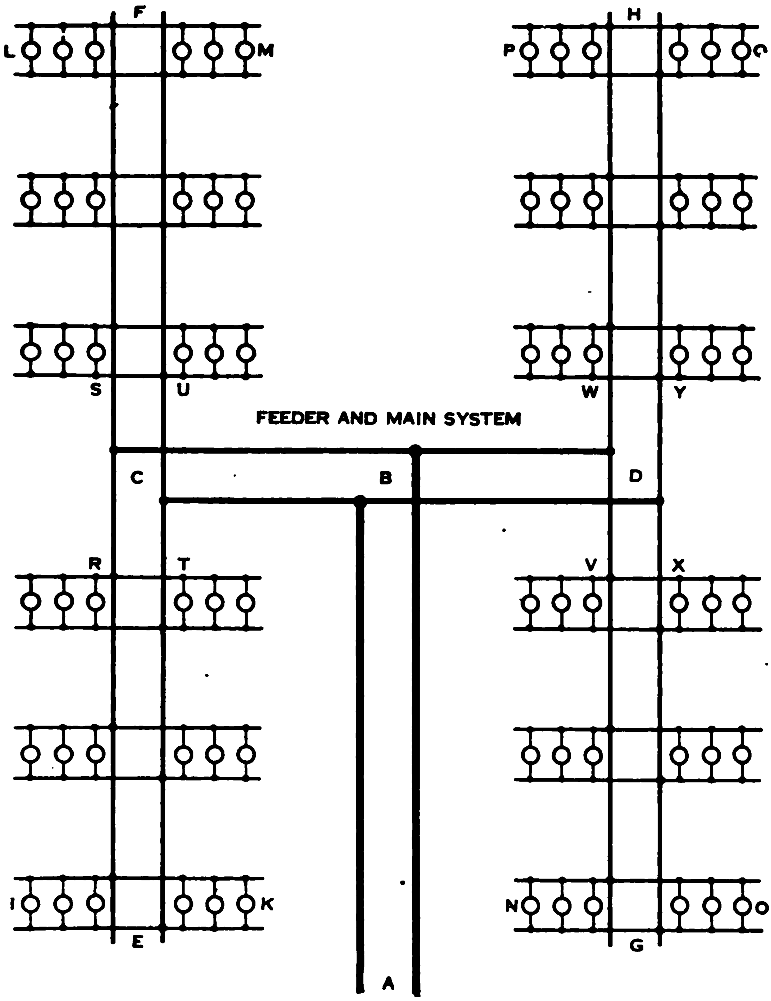


FIG. 180.—Feeder and main or tree system of distribution of wiring for lights.

ably not exceed one volt. Such circuits are shown at *F-I* and *K-L*. A **tap** usually delivers current to a single lamp, motor or other device taking a small amount of current, as in *M*. Fig. 179

does not represent any real installation, but simply shows the relative positions of the different portions of the circuits designated.

Feeder and Main System

When installing wires in buildings there are two general plans of distribution followed. **First,** the **feeder and main,** or **tree** system, illustrated in Fig. 180. Here the source of supply

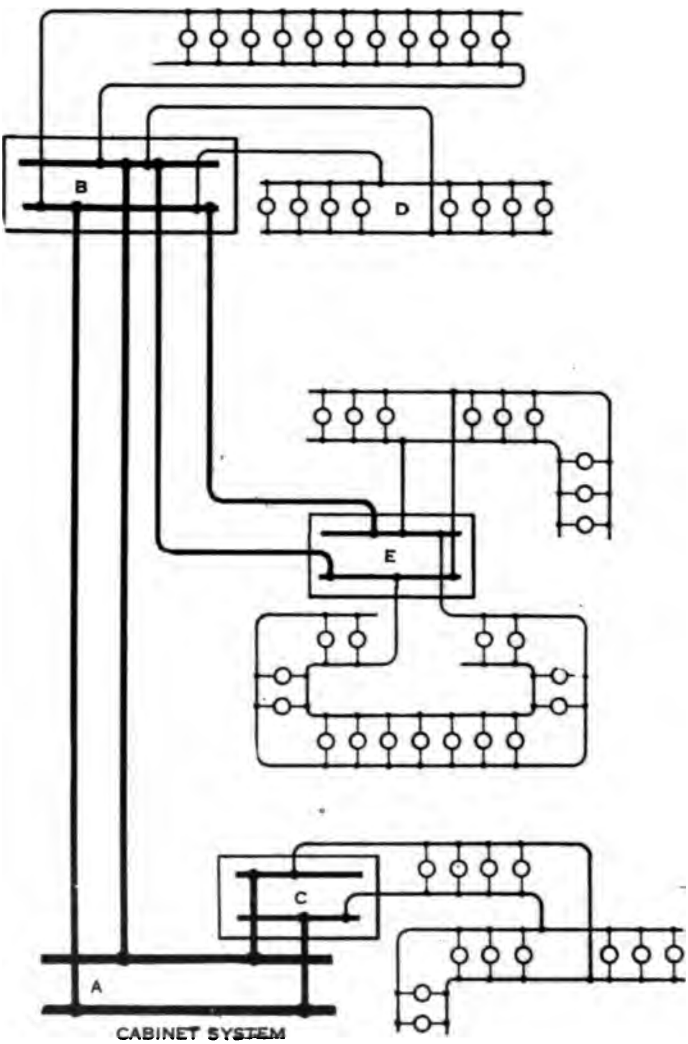


FIG. 181.—Cabinet or closet system of wiring for lights.

enters at *A*, whence a feeder carries the current to the point *B*. The circuit now divides through subfeeders *B-C* and *B-D*. These supply the mains *E-F* and *G-H* respectively. These mains in turn supply branch lines. The general appearance of the system is similar to that of a tree, hence the name. This system is well adapted for obtaining an equality of potentials over the entire installation. Thus, it will be noted that the lamps, *I-K-L-M-N-O-P-Q*, are all equally remote from the source of supply, *A*, and will burn with equal intensity. The lamps *R-S-T-U-V-W-X* and *Y* are all equally close to the source of supply, *A*, and will therefore burn with an equal intensity. Furthermore, the maximum distance between the latter group, which are the nearest, and the former group, which are the farthest removed, is only the distance from the lamp *R* to the lamp *I*. Hence a very uniform brilliancy of all the lamps is assured. It is not possible to secure this layout except in the lighting of large areas, such as convention halls, railroad station plazas or the like. The plan shown contemplates the use of a large number of comparatively small candlepower lamps. With the high candlepower, highly efficient tungsten lamps available today, the extreme subdivision illustrated in the figure would not be considered wise.

Cabinet System

Second, the cabinet system. In wiring office buildings, hotels, and department stores, it is usually convenient to start from a power station in the basement where the power is delivered to the bus bars, *A*, Fig. 181, and then run special lines or feeders to cut-out cabinets, *B* and *C*, conveniently located as distributing centers. From these points subfeeders, *B-D* and *B-E*, may extend to subcabinets or branch lines, from which smaller branches or taps may be taken.

Most installations in large buildings are a combination of the cabinet, and feeder and main system. Thus, there will be a feeder extending from the basement to a cabinet on a particular floor and from that floor a feeder and main system may be extended, or if the floor is not large, branch lines may radiate from the cabinet, each branch supplying no more than 660 watts.

Plans for Securing Uniform Potential

Various methods of securing uniform potential on long lines are shown in Fig. 182. If current enters a long line at the point

A, the lamp nearest this point will burn considerably brighter than the lamp at *B*, due to the natural fall in potential caused by the resistance of the line. If a pair of feeders are employed, which reinforce this circuit at two or more points, as at *C* and

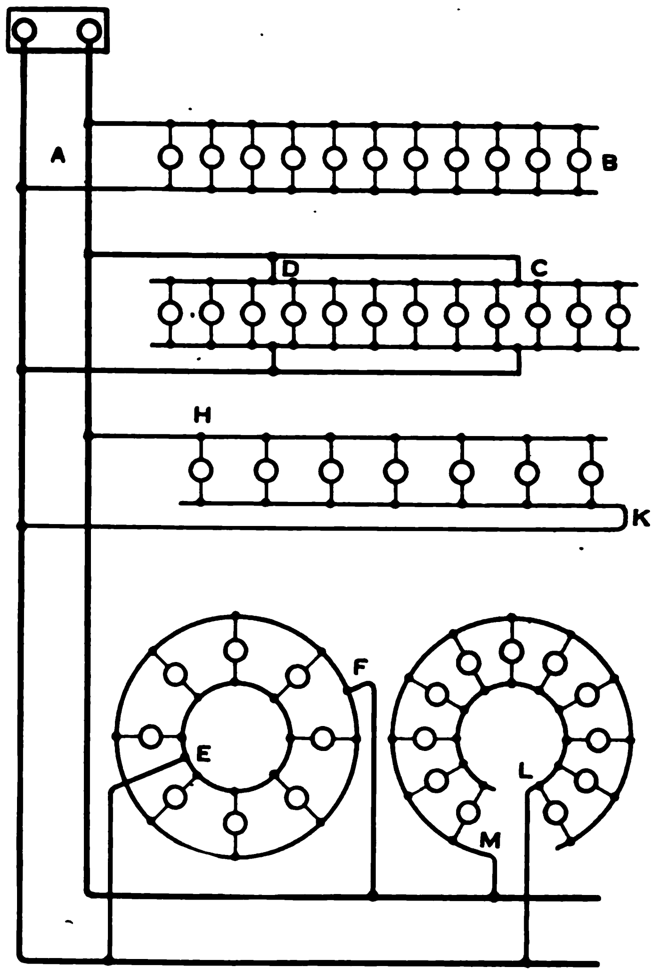


FIG. 182.

D, a very much more uniform potential will be obtained. If lamps are placed in a circle the mains may be fed at *E* and *F* and the loops closed. This insures an even more uniform potential.

Wiedemann System

An ingenious arrangement frequently used for long lines is the **Wiedemann** system, shown at *H-K*. By feeding one end of this circuit at *H* and the other end at *K*, it will be observed that every lamp is connected by exactly the same number of feet of wire with the source. It would therefore be supposed that every lamp would burn with uniform brilliancy. This, however, is not

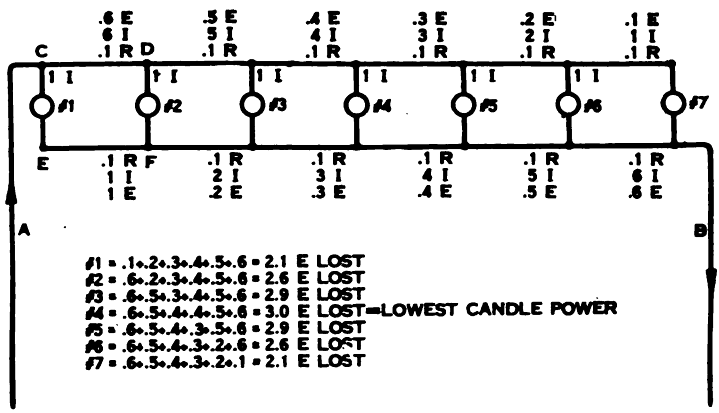


FIG. 183.

the case, for a calculation will show that the middle lamp gets a slightly lower voltage than those at the extreme ends. The above example, Fig. 183, works out this problem in detail. Here lamps are shown numbered from one to seven inclusive. Current is supplied from the mains, *A-B*. The resistance of the line between each two lamps, both on the positive side and the negative side, is taken as 0.1 ohm. The current for each lamp is 1 ampere. It will be evident that if one ampere is supplied to lamp number 1, the section of the line from *C* to *D* will carry the remaining 6 amperes. *E* to *F* will carry one ampere. The current in the succeeding sections of the upper wire diminish one ampere at each section, while those in the lower wire increase one ampere. Multiplying the current by the resistance in each section to get the drop, gives the voltage losses indicated in the figure.

Switches

Groups of lights are usually controlled by means of switches. To turn on or off the lamps on a branch circuit not exceeding

660 watts from one point, a single pole snap switch may be employed. This consists of a blade rotated by a handle, designed to break one wire of the circuit at two points, *S*, Fig. 184.

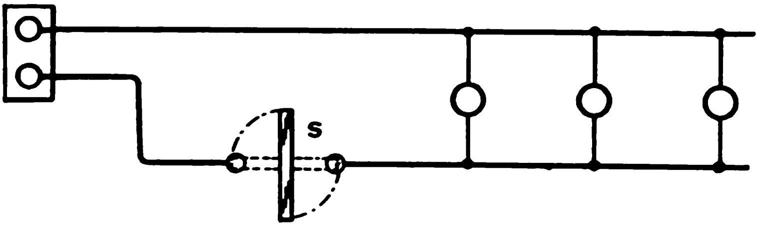


FIG. 184.

The general appearance of this switch is shown in Fig. 185. There is an advantage in severing a circuit at two points in series, Fig. 186. The arc obtained at each of the two points is less than

FIG. 185.

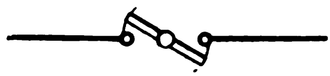


FIG. 186.

FIG. 187.

half that which would be obtained if the circuit were broken at one point only, Fig. 187.

Where a main is to be broken, controlling more than 660 watts, or a branch line, at a cutout cabinet, is to be totally disconnected,

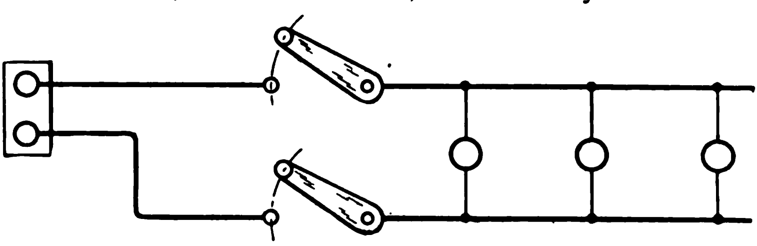


FIG. 188.

double pole switches must be used. These may be either knife switches or snap switches. A double pole switch breaks both wires of the circuit, Fig. 188. Here again each wire may be

broken at one point or at two points in series. Double pole snap switches always break each of the two wires at two points, making four breaks in all. The crossing blades, Fig. 189, are

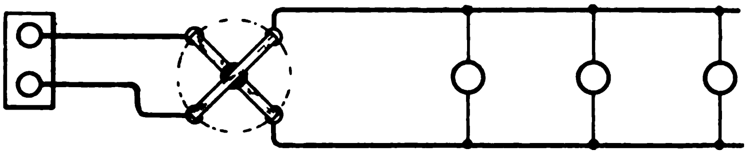


FIG. 189.

insulated from each other, and when rotated by the handle each wire is severed at the two points in series, as shown, for a single wire in Fig. 186. The general appearance of a double pole snap

FIG. 190.

FIG. 191.

switch is shown in Fig. 185. The appearance of a double pole knife switch is shown in Fig. 191.

For controlling lamps from two points independently, three point switches are employed. These are usually snap switches carrying a single blade but having four contacts. Two of these

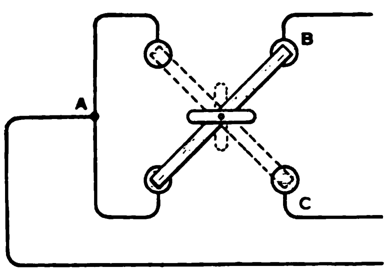


FIG. 192.

contacts are permanently tied together as in Fig. 192. The blade snaps from the position shown in full to the position shown in dotted lines, always tying the common wire, *A*, either to *B* or *C*.

Fig. 193 shows the application of this type of switch to controlling one or more lamps. It is evident that current will flow from *L* to *L'*, through switch *A* and *B* in series in the position shown via the wire *C*. If, now, the switch *A* is snapped into the alternate dotted position, the circuit through *C* is broken, but if the

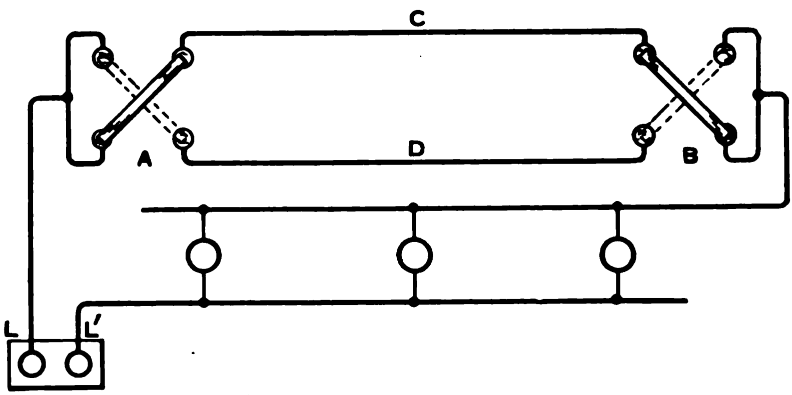


FIG. 193.—Theoretical construction of three point switches for controlling lamps from two points independently.

switch *B* is snapped into the dotted position, the circuit for the lamps is completed through the wire *D*. It is thus possible to turn on or off all the lamps from either *A* or *B*, regardless of the position of the other switch. In the absence of three point switches, double-throw, single-pole knife switches may be employed, Fig. 194. It must be understood that the switch is always to be closed in either the full or the dotted position.

For controlling lamps from more than two points, all switches

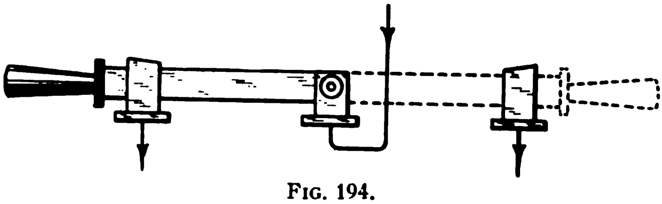


FIG. 194.

except the first and the last in the series must be four point switches. A switch of this sort is shown in Fig. 195. It consists of two blades, rigidly attached to the rotating member, but insu-

lated therefrom and from each other. The switch snaps from the position shown in Fig. 195 to the alternate position shown in Fig. 196, and it always occupies one of these two positions. Thus

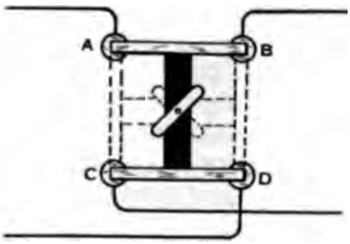


FIG. 195.

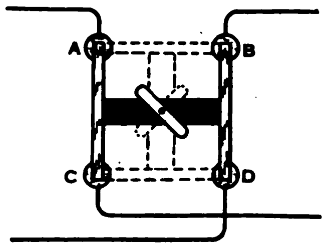


FIG. 196.—Theoretical construction of four point switches for controlling lamps from any number of points independently.

in the first position, lines *A-B* are tied together and lines *C-D* are tied together. In the second, lines *A-C* are connected and *B-D* are connected.

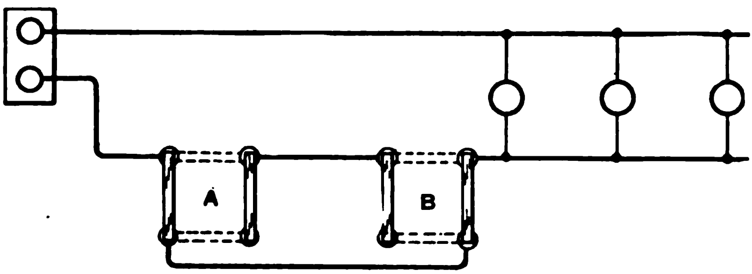


FIG. 197.—Wiring for controlling lamps from two points.

To control lamps from two or more points it is not necessary to use the three point switch at all. It was designed first and has been widely used. However, four point switches may be

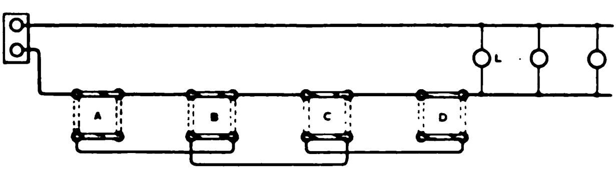


FIG. 198.—Wiring for control of any number of lamps from any number of points independently.

used for controlling lamps from any number of points exclusively. Fig. 197 shows lamps controlled from two points, *A* and *B*, by

four point switches. Either switch snaps from the position shown with the blades vertical to the alternate position with the blades horizontal. Each switch will turn on or off the lamp regardless of the position of the other switch. Fig. 198 shows the four point switches arranged for controlling lamps from any number of points. It will be observed that one wire runs straight through the switches while the other reverses its connections in each switch. It is well worth while to trace the circuit for the lamps at *L* with the switches *A*-*B*-*C*-*D* in various positions. Experiment will show that any switch will turn on and off the lamps regardless of the position of the other switches. In the absence of four point switches,

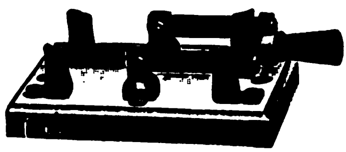


FIG. 199.

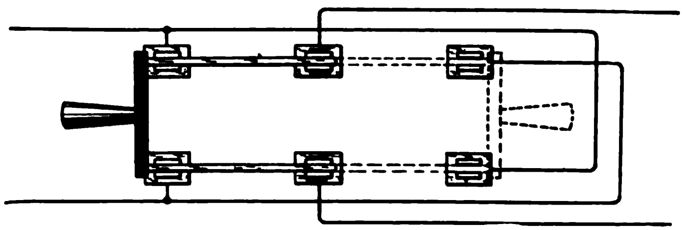


FIG. 200.—Double-pole, double-throw switch used in place of four point switch.

a double pole, double throw knife switch, Fig. 199, may be used instead, wired as shown in Fig. 200. It is understood, of course, that the switch will always be closed in one of the two alternate positions.

SECTION VI CHAPTER III

INTERIOR WIRING

INSIDE WIRING FOR LIGHTS

1. How many different kinds of wiring systems are in common use?
2. Show by diagram, how you would install a flush switch beside a door opening, giving necessary dimensions for locating the switch.
3. Draw a diagram illustrating the use of a single pole snap switch for controlling an incandescent lamp. Draw a similar sketch for a two-pole switch with a large chandelier.
4. How does a four-way switch differ from a three-way switch?
5. Can one or more lights be controlled from more than two points?
6. Draw a diagram illustrating the use of two three-way switches and two four-way switches for controlling two lights from four positions.
7. Why is it not common practice to use four four-way switches in place of two four-ways and two three-ways?
8. Could we use four four-way switches in place of two three-way switches and two four-way switches?

INTERIOR WIRING

THE NATIONAL ELECTRICAL CODE

Some of the Principal Requirements

The National Electrical Code was originally drawn in 1897 as the result of the united efforts of the various Insurance, Electrical, Architectural and allied interests which through the National Conference on Standard Electrical Rules, composed of delegates from various National Associations, unanimously voted to recommend it to their respective associations for approval or adoption.

General Suggestions

In all electric work, conductors, however well insulated, should always be treated as bare, to the end that under no conditions existing or likely to exist can a ground or short circuit occur, and so that all leakage from conductor to conductor or between conductor and ground, may be reduced to the minimum.

In all wiring, special attention must be paid to the mechanical execution of the work. Careful and neat running, connecting, soldering, taping of conductors, and securing and attaching of fittings, are especially conducive to security and efficiency and will be strongly insisted upon.

In laying out an installation, except for constant-current systems, every reasonable effort should be made to secure distribution centers located in easily accessible places, at which points the switches and cutouts controlling the several branch circuits can be grouped for convenience and safety of operation. The load should be divided as evenly as possible among the branches, and all complicated and unnecessary wiring avoided.

The use of wire-ways for rendering concealed wiring permanently accessible is most heartily endorsed and recommended, and this method of accessible concealed construction is advised for general use.

Architects are urged when drawing plans and specifications to make provision for the channeling and pocketing of buildings for electric light and power wires.

Generators must be located in dry places. When operating at

a pressure in excess of 550 volts, they must have their base frames thoroughly grounded. When operating at less than this potential their base frames must be grounded if practicable. If, however, this is not feasible, special permission may be given for its omission, in which case the base frame must be permanently insulated.

Constant Potential Generators (except alternating current machines and their exciters) must be protected from excessive current by fuses or equivalent devices of approved design.

Conductors from generators to switchboards, rheostats or other instruments and thence to outside lines must be in plain sight or readily accessible. Bus bars may be made of bare metal. All wires for ground detectors, voltmeters, pilot lights and potential transformers must be of not less than No. 14 B. & S. gauge wire, this circuit to be protected by approved fuses and not to carry over 660 watts.

Switchboards must not be built up to the ceiling. A space of at least 3 feet should be left, if possible, between the ceiling and the board. The board should also stand some distance out from the wall, back of it.

Switchboards must be made of non-combustible material. If the wiring is placed on the back of the board there should be 18 inches at least between the wall and the switchboard. If the wiring is on the front of the board, the board may be placed against the wall, although it is preferable to have it set out.

Resistance boxes must be placed on switchboards or if not thereon, at a distance of at least a foot from any combustible material, or separated therefrom by non-combustible, non-absorptive material such as slate or marble.

Lightning arresters must be attached to each wire of every overhead circuit connected with a station. They must be located in readily accessible places, away from combustible materials and as near as practical to the point where the wires enter the building, preferably not on the switchboard. Arresters must be connected to a permanent ground connection by metallic strips or wires at least equal to No. 6 B. & S. copper. These conductors should run in as nearly a straight line as possible from the arresters to the ground. Such ground wires must not be attached to gas pipes within a building. Ground wires should under no circumstances be led through an iron pipe to the ground

Motors.—The insulation or grounding of the frames of generators applies equally to motors.

The leads or branch circuits running to motors must be designed to carry a current at least 25% higher than that for which the motor is rated.

Every motor and starting box must be protected by cutout and controlled by a switch, said switch plainly indicating whether on or off.

With ¼ h.p. motors or less on circuits of 300 volts or less, single-pole indicating snap switches may be used. Switch and starting box must be located within sight of the motor except by special permission.

Motors must not be run in series-multiple or multiple-series except on constant potential systems and then only by special permission.

Outside Work

Service wires between main cutout and switch, and the first support from the cutout or switch on outside of building must have an approved rubber insulating covering, but from this support to the line (except when run in conduit) may have an approved weatherproof insulating covering.

Outside wires must be placed 8 feet above the highest point of roofs over which they pass or to which they are attached.

They must be so spliced as to be both mechanically and electrically secure without solder. The joints must then be soldered to insure preservation and covered with an insulation equal to that on the conductors.

Service wires entering buildings must have drip-loops outside the holes through which the conductors pass. These holes must be bushed with non-combustible, non-absorptive insulating tubes, slanting upward toward the inside. For low potential systems, service wires may enter buildings through a single iron conduit, the conduit to be equipped with an approved service head. The inner end must extend to the service cutout, and if a cabinet is required by the "Code" must properly enter the cabinet.

Where transformers are connected to high potential circuits it is desirable for protection of life and property that the secondary system be permanently grounded.

The neutral point on a direct current three-wire system should

be permanently grounded at the central station. The ground connection must include all available underground complete metallic piping systems. The neutral wire of overhead systems should be grounded every five hundred feet.

The secondaries of transformer distributing systems should be grounded at a neutral point if a wire at such a point is accessible. If not, one of the outside wires may be grounded provided the difference of potential between the ground and any other point on the circuit does not exceed 150 volts.

Inside Work

Wires for all systems and voltages must not be smaller than No. 14 B. & S. gauge except for flexible cord pendants carrying a single light or for the wiring of electric or gas fixtures between the pipe and the casing. In these two latter cases wires as small as No. 18 gauge may be used.

Tie wires must have an insulation equal to that of the conductors they confine. The use of split knobs which dispense with tie wires is recommended where the wire is smaller than No. 8 B. & S.

Wires must be so spliced as to be mechanically and electrically secure without solder. The joints must then be soldered to insure preservation and covered with an insulation equal to that of the conductors.

Stranded wires, except flexible cords, must be soldered before being fastened with clamps or binding screws and whether stranded or solid when they have a conductivity greater than No. 8 B. & S., they must be soldered into lugs for all terminals.

For all wires larger than No. 4 B. & S., split knobs (single-wire cleats) must have provision for two supporting screws.

Wires must be separated from contact with walls, floors, timbers or partitions through which they may pass by non-combustible, non-absorptive insulating tubes such as glass or porcelain, except at outlets. They may be threaded through "circular loom" or equivalent tubing to pass through the outlet. Wires must be kept free from contact with gas, water or other metallic piping, or other conductors which they cross by some continuous fixed non-conductor, creating a permanent separation. Wires must be so placed in wet places that an air space will be left between conductors and pipes and they should be so run that they cannot come in contact accidentally. Wires

should be run over, rather than under, pipes upon which moisture is likely to gather.

Wires must not be installed in wooden mouldings or upon porcelain insulators in elevator shafts. Metal conduits only, or armored cables are approved in such cases.

For insulated **aluminum wires** the safe carrying capacity is 84% of that given in the following table for copper wire, with the same kind of insulation.

Carrying Capacity of Wires

B. & S. gauge.	*Rubber insulation*	*Other insulation*
18	3 amperes	5 amperes
16	6	10
14	15	20
12	20	25
10	25	30
8	35	50
6	50	70
5	55	80
4	70	90
3	80	100
2	90	125
1	100	150
0	125	200
00	150	225
000	175	275
0000	225	325

The lower limit is specified for rubber-covered wires to prevent gradual deterioration of the insulation by heat. The carrying capacity is based upon the comparative heat radiating abilities of the different gauge numbers and the ultimate temperature to which they are likely to rise. The question of potential drop is not taken into consideration in the above values.

Switches, cutouts and circuit breakers must be arranged so as to simultaneously break all the wires of a circuit.

Automatic cutouts must be placed on all service wires as near as possible to the point where they enter the building, and arranged to cut off the entire current.

Cutouts must be placed at every point where a change is made

in the size of wires unless the cutout in the larger wire will protect the smaller. Cutouts must be in plain sight or encased in approved cabinets and readily accessible. They must not be placed in the canopies of fixtures.

The old-fashioned porcelain link-fuse cutout is not approved. Link fuses cannot be used except when mounted on slate or marble bases and enclosed in tight fireproof cabinets.

Cutouts must be so placed that no circuit requiring more than 16 medium-sized sockets or 25 candelabra size sockets or lamp receptacles requiring more than 660 watts will be dependent upon any cutout, except in cases of large chandeliers, stage-lights and illuminated signs.

Switches must be placed on all service wires in a readily accessible place as near as possible to the point where wires enter the building, and arranged to cut off the entire current.

Single-throw knife switches must be so placed that gravity will not tend to close them. When possible, switches should be so wired that the blades will be dead when the switch is open.

Single-pole switches must never be used as service switches or for the control of outdoor signs or circuits located in damp places. They are allowed only on two-wire branch or tap circuits supplying not more than 660 watts.

Three-way switches are considered as single-pole switches.

No push-buttons for bells or gas-lighting shall be placed on the same wall plate with switches controlling electric lights or power.

Low potential systems include all wiring and devices operating at from 0 to 550 volts.

High potential systems include all wiring devices operating at from 550 to 3,500 volts.

Extra high potential systems include all wiring devices operating at over 3,500 volts.

Low Potential Inside Wiring

Wires upon inside low potential systems must not be laid in plaster or cement or similar finish and must not be fastened with staples.

Twin wires must never be used except in conduits or where flexible conductors are necessary.

Wires must be protected on side walls from mechanical injury.

For open work in dry places wires must have an approved rubber or slow-burning weatherproof insulation.

They must be rigidly separated on non-combustible, non-absorptive insulators which will separate the wires from each other and from the surface wired over as follows:

Up to 300 volts the wires must be separated ½ inch from the wall and 2½ inches from each other. Cleats or knobs used to support wires must be not over 4½ feet apart when supported on knobs supporting the wire one inch from the surface wired over.

For open work except in dry places, all inside wires must have an approved rubber insulation. Where porcelain knobs are used exclusively for open work, wires of opposite potential must be 4 inches apart. If placed in cleats they may be 2½ inches apart.

Interior conduits must be continuous from outlet to outlet or to junction boxes and the conduit must be properly secured to all fittings. No conduit of less than half-inch electrical trade size shall be used. Conduits must first be installed completely without wires. They must be equipped with approved outlet boxes or plates at every outlet. They must be provided at all outlets with approved bushings fitted so as to protect wires from abrasion.

The metal of conduits must be permanently and effectually grounded.

All wires placed in metal conduits must have an approved rubber insulating covering. They must be double-braided for twin, twisted pair or multiple conductor cables and for all single conductors of No. 6 or larger. They must not be drawn in until all mechanical work on the building has been completed. In vertical conduits, conductors must be supported by a turn in the conduit or in some other way every 35 to 100 feet according to the size of the conductor.

Junction boxes must always be installed in such a manner as to be accessible. All elbows and bends in a conduit must be made so that the pipe will not be injured. The radius of any curve on the inner edge must not be less than 3½ inches. There must not be more than the equivalent of four quarter bends between any two outlets, the bends at the outlets not being counted.

Size of Conduits for the Installation of Wires and Cables
Number of Conductors in System

(Electrical Trade Size of Conduit Given in Inches.)

Size B. & S.	One conductor in conduit	Two conductors in conduit	Three conductors in conduit	Four conductors in conduit
14	½	½	½	¾
12	½	¾	¾	¾
10	½	¾	¾	1
8	½	1	1	1
6	½	1	1¼	1¼

Metal moulding must be continuous from outlet to outlet, to junction boxes, or to approved fittings designed especially for use with metal mouldings, and must at all outlets be provided with approved terminal fittings which will protect the insulation of conductors from abrasion.

Where such moulding passes through a floor it must be carried through an iron pipe extending from the ceiling below to a point five feet above the floor, unless the moulding is sufficiently strong mechanically, in which case the pipe need extend only 3 inches above the floor.

Metal mouldings may be passed through partitions without the surrounding iron pipe, providing partition is dry and there is no break in the moulding within the partitions.

The junction boxes used with metal mouldings and gas pipes must all be secured together so as to make a good electrical connection.

Connections to grounded pipes and metal mouldings must be exposed to view or accessible. Only approved ground clamps shall be used.

Armored cables must be continuous from outlet to outlet or to junction boxes or cabinets, and the armor of the cable must properly enter and be secured to all fittings.

They must be equipped at every outlet with an approved outlet box or plate as required in conduit work. Outlet plates must not be used if it is practicable to install outlet boxes.

The metal armor of cables must be securely grounded to water piping, gas-piping or other suitable grounds. If grounded, the gas-pipe connections must be on the street side of the meter. If the armored cable system consists of several separate sections of cable, the sections must be bonded to each other, and the system grounded or each section may be separately grounded.

Whenever exposed to moisture, such cables must have a lead covering between the outer braid of the conductors and the steel armor. The lead covering is not required, however, where the cable is run against brick walls or laid in ordinary places, unless same are continuously damp.

The two conductors of a circuit must always be encased in the same armor when alternating current is to be employed as is the case with conduit systems or wherever a metal coating surrounds the conductors.

Flexible cord must have an approved insulation and covering. It must not be used as a support for clusters. It may be used for pendants, wiring of fixtures, portable lamps or motors and portable heating apparatus. Cord adjusters for looping up and adjusting the length of flexible cord pendants must not be used except when reinforced cord is employed. This consists of the ordinary flexible cord covered with an additional reinforcement of rubber and braid. Flexible cord must not be used in show windows. The cord must always be protected by insulating rubber bushings where the cord enters the socket of a pendant lamp. Such lamps must be so suspended that the entire weight of the socket and lamp will be borne by a knot or other device under the bushing in the socket and above the point where the cord comes through the ceiling rosette in order that all strain may be taken from the joints and binding screws.

All wires in either metal or wooden moulding must have an approved rubber-insulated covering and must be in continuous lengths from outlet to outlet or from fitting to fitting. No joints to be made in moulding.

Neither wooden nor metal moulding will be permitted in damp places, nor will such moulding be permitted in any case where the potential difference is more than 300 volts. When an installation of metal moulding is being made, permission will be given to extend it through walls and partitions if the moulding and capping are in continuous lengths where it passes through.

Not more than four No. 14 wires and no single circuit of more than 1,320 watts shall be used in metal moulding.

Concealed Knob and Tube Work.—Where wires are installed in concealed knob and tube work, only an approved rubber insulating covering is permitted.

They must be rigidly supported on non-combustible, non-absorptive insulators which separate the wire 1 inch from the surface wired over. They should be run singly on separate timbers or studding and must be kept at least 5 inches apart.

They must be separated from contact with walls, floors, timbers, and partitions through which they pass by non-combustible, non-absorptive insulating tubes, such as glass or porcelain.

Rigid supporting requires supports at least every 4½ feet along a flat surface. At distributing centers, outlets and switches where space is limited and the 5-inch separation cannot be maintained, each wire must be separately encased in a continuous length of approved flexible tube, such as "circular loom."

When it is impracticable to place the entire circuit on non-combustible supports, as above, that portion which cannot be so supported must be installed with approved metal conduit or approved armored cable, except that if the voltage is not over 300 and the wires not exposed to moisture they may be fished if separately encased in approved flexible tubing, such as "circular loom," extending in continuous lengths from the last porcelain support to the outlet.

When using either conduit or armored cable in mixed concealed knob and tube work, the requirements for conduit work or armored cable work must be complied with.

In concealed knob and tube work, the wires extending to an outlet must be protected by approved flexible tubing extending in continuous lengths from the last porcelain support to at least one inch beyond the outlet.

Fixtures

When fixtures are supported at outlets in metal conduit, armored cable or metal moulding systems, or from gas-piping or any grounded metal work or when installed on metal walls or ceilings or on plaster walls or ceilings containing metal lath, or on walls or ceilings in fireproof buildings, they must be insulated from such supports by approved insulating joints placed as close as possible to the ceilings or the walls. The insulating

joint may be omitted in such systems where straight electric fixtures are employed provided the insulation of the conductors in the fixtures is the equivalent of the insulation in other parts of the system and provided that approved sockets, receptacles or wireless clusters are used, having porcelain or equivalent insulation between live metal parts and outer metal shells.

Gas-pipes must be protected above the insulating joint by approved insulating tubing. And where outlet tubes are used they must be of sufficient length to extend below the insulating joint and must be so secured that they will not be pushed back when the canopy is put in place.

Where insulating joints are required, fixture canopies of metal must be thoroughly insulated from metal walls, ceilings or plaster walls on metal lathing and from outlet boxes.

When fixtures are installed out-of-doors, they must be of water-tight construction.

The wires used inside of fixtures must not be smaller than No. 18 and must have an approved insulated rubber covering.

When fixtures are wired on the outside they must have the conductors so secured as not to be cut or abraded by the pressure of the fastenings nor the motion of the fixture.

Fixtures with the wiring on the outside must not be used in show windows.

Chain fixtures must be wired with flexible conductors.

Wires of different systems must never be contained in or attached to the same fixture.

Fixtures must be free from short-circuits between conductors and from contact between conductors and metal parts of fixtures and must be tested clear before being connected to the source of supply.

SECTION VI CHAPTER IV

INTERIOR WIRING

THE NATIONAL ELECTRICAL CODE

1. What is the National Electrical Code and how did it originate?
2. How should all electrical conductors be treated?
3. What constitutes a good electrical installation?
4. When must the frames of generators be grounded?
5. When must generators be protected by fuses or equivalent devices?
6. What distance should be maintained between the top of a switchboard and the ceiling?
7. What precautions should be taken in mounting switch boxes?
8. What size ground conductor should be used in grounding lightning arresters?
9. How should every motor be protected when installed?
10. Is it permissible to use a single pole switch for the control of a motor?
11. What is a drip loop and what is its purpose?
12. When should the neutral wire of an overhead system be grounded?
13. What is the smallest wire permitted in interior wiring? What is the smallest wire permitted in fixture wiring?
14. When must lugs be used in connecting wires to switch terminals, etc.?
15. What are the requirements for a splice?
16. How must wires be protected when passing through walls, partitions and joists?
17. What is the carrying capacity of No. 14 wire with rubber insulation?
18. What is the maximum number of outlets permitted on a single circuit in interior wiring? What is the maximum wattage allowed?
19. What is the proper location for the entrance and cutout in a building?
20. What voltage is considered high potential?
21. In open work what separation must be maintained between the wires and the surface wired over?
22. How far apart should supports be spaced?
23. What two kinds of conduits are in general use?
24. What is the smallest size conduit allowed in interior wiring?
25. When is it necessary to ground a conduit system?
26. When must double braid wire be used in conduit?
27. What is the inner radius of a bend in conduit?
28. What type of insulation should be used in concealed knob and tube work?
29. What separation must be maintained between the wires?
30. When is the use of circular loom permitted?
31. When must fixtures be supplied with insulated canopies?
32. When must fixtures be supplied with insulating joints?

INSTRUMENTS AND MEASUREMENTS

SIMPLE GALVANOMETERS

A galvanometer is an instrument for measuring the strength of an electric current by means of the magnetic effect which the current produces. An electroscope detects an electric charge. An electrometer measures the quantity of the electric charge. A galvanoscope detects an electrical current. A galvanometer measures the strength of the current.

Galvanometers may be classified under three heads. **First,** those employing a fixed coil and a movable magnetic needle. **Second,** those employing a fixed magnet and a movable coil. **Third,** those employing a fixed coil and a movable coil without a magnet. The latter instrument is designated as an "electro-dynamometer."

To prevent a weak current from deflecting the moving member as far as a strong current, it is necessary to provide some method of control. There are four principal methods.

Control by Earth's Magnetism

First, the earth's magnetism. If a needle, *A*, Fig. **201**, is placed in the earth's field, it will take up the direction *A-B*. If, now, a current is applied to a coil surrounding the needle, it tends to deflect this needle in the direction *C*. The needle will

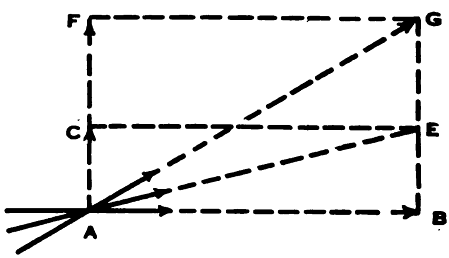


FIG. 201.

turn from its normal position toward *C*. The actual direction which it will assume depends upon the relative intensity of the two forces. If the direction and length of the line *A-B* represents the direction and intensity of the earth's magnetism while the line *A-C* represents the direction and intensity of the mag-

netic field due to the current, the needle will take up a resultant direction, *A-E*, which is the diagonal of a parallelogram of forces in which the components are *A-C* and *A-B*. If a stronger current passes through the coil, the deflecting force may be increased to *A-F*. The intensity of the earth's magnetism does not change. The needle will now turn from the position *A-E* and take up the direction *A-G*, which is the diagonal of the new parallelogram, of which the components are *A-F* and *A-B*.

Control by Torsion of a Wire

The second method of control is by the torsion of a wire. Instruments of the second class, the moving member being a coil, are not subject to control by the earth's magnetism. The coil is therefore suspended by a fine phosphor-bronze wire or flat strip. When the coil is deflected by a current passing through it, this suspending strip is twisted and the torsional stress increases with the deflection.

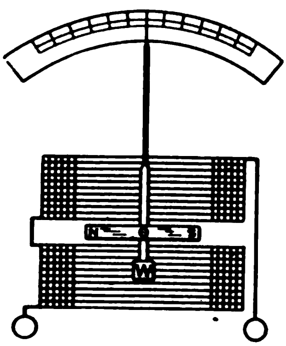


FIG. 202.—Lecture table galvanometer.

Control by Gravity

The third method of control is by gravity. In some forms of galvanometer used for lecture table purposes, the magnetic needle is suspended horizontally, as in Fig. 202. A light aluminum index extends vertically above the coil and moves back and forth across a scale. A counter weight, *W*, keeps the bar, *N-S*, horizontal and the index at the center of the scale. When a current passes through the coil the bar tries to assume a vertical position, so as to align its flux with the flux of the coil. In so doing the center of gravity is raised.

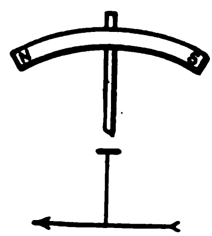


FIG. 203.

Control by Permanent Magnet

The fourth method of control is by a permanent magnet. In some instruments it is not practical to employ the earth's magnetism as one of the two forces in a galvanometer. It is desirable to have the needle assume a definite position without regard to the position of the instrument in the earth's field. The

needle can be definitely controlled by placing a permanent magnet either below or above the needle, as in Fig. 203. This magnet is capable of rotation and the needle is deflected by the current in the coil.

Methods of Observation

The measurement of electric current by a galvanometer is really the measurement of the magnetic force produced by the current. The methods of measuring the current, therefore, are similar to those employed for measuring magnetic force. There are several methods of observation which may be employed in connection with galvanometers.

The deflection method.—The needle is deflected through a certain angle by the application of the current. The deflection

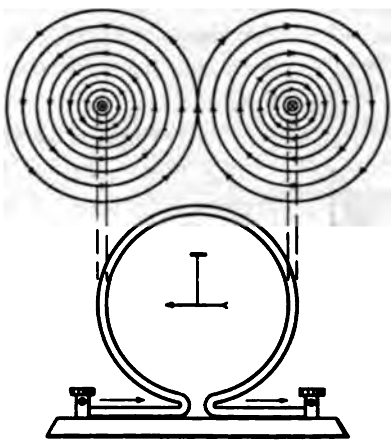


FIG. 204.—Tangent galvanometer.

in degrees is observed. This deflection is a measure of the strength of the current, and is a common method of observation. It should be noted, however, that the angle of deflection is proportional to the strength of the current through a limited number of degrees only. It is not practical to construct a simple galvanometer in which the angle of deflection is proportional to the strength of the current, but it is practical to build one in which the **tangent** of the angle of deflection is proportional to the current. Such an instrument is known as a tangent galvanometer and is shown in Fig. 204. Here a short needle is suspended in the center of a coil of relatively large diameter, consisting of a

single convolution. The object of this large coil is to insure that the needle will move in a uniform field. This is not a very sensitive instrument but its indications are quite accurate. The principle upon which it operates will be understood by a study of the diagram, Fig. 205. Here, let the directive force of the earth's magnetism be represented by the line *C-E*, and the deflecting force due to the current be in the direction *C-D*. If a current of one ampere in this direction is measured by the line *E-F*, the needle will deflect through the angle *E-C-G*. Two amperes would be measured by just twice the distance along the line *A-B*, or the distance *E-H*. The needle now deflects through the angle *E-C-I*. It will thus be observed that for each equal increase in current value, the deflecting force will be measured by an equal increase along the line *E-B*, but the angle through which the needle turns, for each successive increase in current, becomes less and less. Thus, with thirteen amperes of current the needle would deflect in the direction *C-13*. It would be obviously impossible for the needle ever to be deflected 90 degrees, for the line *A-B* is parallel to the line *C-D* and could never meet it.

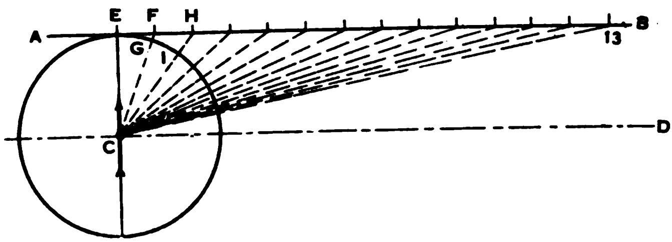


FIG. 205.

The torsion method of observation is employed in the electrodynamometer shown in Fig. 206. Here the moving coil, *M*, is suspended by a silk thread, and connected with the torsion head by means of a spiral spring, *G*, Current is admitted to a stationary coil, *F*, and thence in series with the moving coil *M* through mercury cups, *C-C*. The current causes this coil *N* to turn in an effort to set itself parallel with the first coil, *F*. This causes the index, *N*, to swing aside. By turning the torsion head, *T*, in the opposite direction to that in which the coil is deflected the coil may be restored to the starting point against the deflecting force of the current. When the deflecting force

of the current is exactly balanced by the torsion of the wire, the degrees of torsion on the head of the instrument are an exact measure of the force. This is a very accurate method of observation. The instrument is employed for measuring alternating currents. As the two coils of the electro-dynamometer are in series, the force with which they tend to align themselves with each other is proportional to the product of the current strength in one and the current strength in the other. Thus, if a current of two amperes passes, the force with which the moving coil tends to turn is not proportional to two, but is proportional to 2 times 2 or 4. If the current increases to 4 amperes, the strength of the stationary coil is doubled and the strength of the moving coil is doubled. This makes the strength between the two coils equal to 4 times 4 or 16. Now, while it is true that the degree of torsion on the head of the instrument is an exact measure of the force, this force is proportional to the square of the current, because the two coils are in series. Therefore, to get an indication of the current in amperes in any case it is necessary to extract the square root of the degrees of torsion. To use this instrument for measuring current strength it is first necessary to determine its constant.

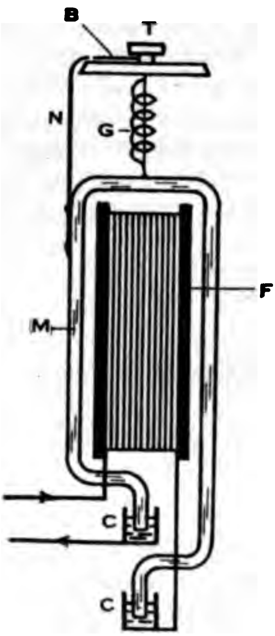


FIG. 206.—Siemens' electro-dynamometer.

To do this the instrument is connected in series with a standard ammeter and full rated current passed through the circuit. The dynamometer is balanced for this current. This current in amperes, divided by the square root of the deflection, gives the constant of the instrument. This constant is the amount of current required to balance the coil in the zero position against one degree of torsion.

Thereafter the value of any current may be obtained by taking the square root of the degrees of torsion and multiplying by this constant. Thus,

$$I = \sqrt{D} \times K$$

The **ballistic** or **first swing** method of observation is a method employed for measuring transient currents such as those produced by the discharge of a condenser. If a magnetic needle is allowed to swing without any restraining force, it is found that the ultimate deflection to which it will settle down is just one-half of the first swing. The needle in an instrument of this sort is sometimes encased in lead in order that it may not move appreciably before it has received the full impact due to the condenser's discharge. Now, although the current has ceased, the needle having absorbed the energy of the discharge, starts on its trip. The ultimate deflection to which it would subside if the current had been continued would be just one-half of the first swing. It is, therefore, only necessary to carefully observe the ultimate deflection of the first swing and then take one-half of this amount for an indication of the actual current strength.

The cumulative method of observation is useful in the measurement of very minute currents. If the current is so feeble as not to produce a measurable deflection, the circuit may be opened and closed periodically. The successive closures should be timed to correspond to the natural period of oscillation of the needle. Very feeble currents may thus be employed to build up a measurable deflection.

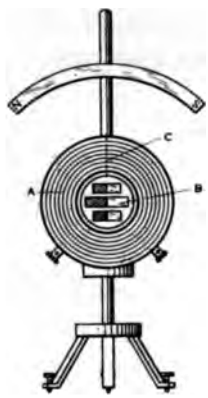


FIG. 207.—Thompson's long coil reflecting galvanometer.

The null method.—In certain combinations of electrical circuits, such as the Wheatstone Bridge, it is desirable to obtain a balance of electro-motive-forces so that no current flows through the galvanometer. The needle will deflect in one direction or the other at all times except when the exact balance desired is obtained. This is called the "null method" of observation.

With reference to the winding, galvanometers may be classed as follows:

Long coil galvanometers, in which the instruments contain many convolutions of fine wire. They are designed for measuring very minute currents of some appreciable voltage. An instrument of this sort is pictured in Fig. 207. It has a resistance of more than 100 ohms. A current produced by dipping

a steel needle and a brass pin in a drop of salt water will produce a measurable deflection on such an instrument.

Short coil galvanometers are those which contain but few convolutions of coarse wire. The electro-dynamometer illustrated in Fig. 206 is an instrument of this class. It is designed for measuring currents of some appreciable amperage but very minute voltage. If a strip of lead is soldered to a strip of copper and the juncture is heated, there will be generated a minute electro-motive-force. This e.m.f. will be proportional to the excess of temperature of the juncture above the rest of the circuit. This is called a thermo-electric couple. A short coil galvanometer of proper design will detect such a current. This galvanometer has a resistance of but a small fraction of an ohm.

If the needle and pin battery was connected to the short coil galvanometer and the thermo-electric couple connected to the long coil galvanometer, neither instrument would show an appreciable deflection. This emphasizes the importance of selecting a suitable type of instrument for a given amount of current.

SECTION VII — CHAPTER I

INSTRUMENTS AND MEASUREMENTS

SIMPLE GALVANOMETERS

1. Define a galvanometer.
2. Into what three classes are galvanometers divided?
3. Distinguish between electroscopes and electrometers; galvanoscopes and galvanometers.
4. Why is it necessary to have some method of control for a galvanometer?
5. State four methods of control employed in galvanometers.
6. Mention the various methods of observation employed with galvanometers.
7. Explain the deflection method of observing the reading of a galvanometer.
8. Explain the torsion method of observing the reading of a galvanometer.
9. Explain the first-swing or ballistic method of observing the reading of a galvanometer.
10. Explain the cumulative method of observing the reading of a galvanometer.
11. Explain the null method of observing the reading of a galvanometer.
12. Explain the principle of the tangent galvanometer.
13. Explain the principle of the Siemen's electro-dynamometer.
14. Explain the construction of a long-coil galvanometer. For what kind of currents is it adapted?
15. Explain the construction of a short-coil galvanometer. For what kind of currents is it adapted?

INSTRUMENTS AND MEASUREMENTS

TYPES OF GALVANOMETERS

Galvanometer Shunts

Thompson Galvanometer.—One of the earliest sensitive galvanometers was designed by Sir William Thompson. It is known as Thompson's mirror galvanometer and is shown in Fig. 207. It consists of a fine wire coil, *A*, having a resistance of one hundred ohms or more, in the center of which is suspended a magnetic system. This consists of two or three pieces of watch spring, *B*, hardened and highly magnetized, with their north poles all pointing in one direction and constituting a powerful compound magnet of great strength for its size and weight. These pieces are glued to the back of a small concave mirror and the whole is suspended by a single strand of cocoon fiber, *C*. Above the coil is a curved permanent magnet, *N-S*, which is used to direct the magnetic needle to a position parallel with the coil. A light beam is thrown upon the mirror and is reflected upon a scale placed about 3 feet away. This beam constitutes a long pointer without weight and serves to show in a magnified way the least motion of the suspended system. This form of galvanometer was the first type used for receiving transatlantic messages over ocean cables.

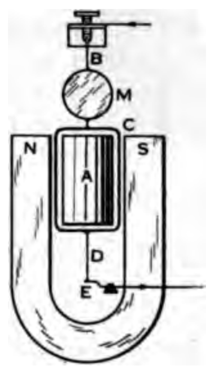


FIG. 208.—D'Arsonval galvanometer.

D'Arsonval Galvanometer.—A very widely used form of galvanometer is the D'Arsonval instrument, shown in Fig. 208. Here a powerful permanent steel magnet, *N-S*, horseshoe in form, and often made with a laminated structure, is mounted with its poles in a vertical position. Between these poles and rigidly supported from the rear, is a soft iron core, *A*, cylindrical in form. This is employed to concentrate the magnetic flux between the poles. Suspended in the narrow gaps between the magnet and core is a small coil, *C*, hung by a fine phosphor-bronze strip, *B*, which serves as a method of control and at the

same time to admit current to the moving coil. The current is taken out by a similar wire, *D*, which, aided by the spring *E*, serves to keep the coil under sufficient tension to prevent its striking the magnet or core. The coil varies in resistance according to the application of the instrument. An index is sometimes attached to the coil, which shows the deflection upon a scale, but more generally a mirror, *M*, is employed to reflect a light beam upon a scale of greater range. When the current is admitted to the coil *C*, it tends to turn in accordance with Maxwell's rule. Its normal position is such that the permanent magnetic flux passes parallel to the winding. As soon as current is introduced the coil moves in an attempt to place itself at right angles to the position shown in the figure, in order that it may enclose within its embrace the magnetic flux of the magnet. This instrument superseded the Thompson mirror galvanometer for receiving cable messages. It was found possible to attach a lever to the coil, *C*, which was connected with a source of ink supply so that the message could be traced upon a tape. It was known as the siphon recorder.

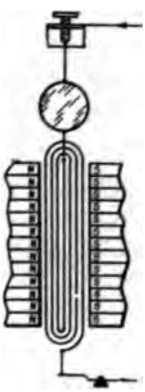


FIG. 209.—Ayrton and Mather galvanometer.

Ayrton and Mather Galvanometer.—A modification of D'Arsonval's instrument, devised by Ayrton and Mather, is shown in Fig. 209. An end view of a powerful laminated permanent magnet is shown. In a narrow crevice between the opposite poles of this magnet is mounted a circular copper coil without a core. Current is admitted to and collected from the coil by means of phosphor-bronze suspending wires and a mirror is used to indicate the deflection. Both this and the preceding instrument are frequently known as the D'Arsonval type. This name is commonly applied to all suspended coil instruments.

Damping

In order that galvanometers may not require too long a time for their oscillations to subside, some form of damping device must be used. Instruments may be damped in one of the three following ways: First, by an **air damper,** where an aluminum vane or fan is attached to the moving system and is arranged to swing in a semi-airtight chamber. The resistance offered by the

air brings the system to rest quickly. Second, by means of **oil,** in which the air chamber referred to above is filled with oil and the damping is much more severe. Oil damping is not generally practical because the oil gives trouble at different temperatures and the instrument is not portable. Third, **electro-magnetic damping,** which is most widely used. A true damper must not interfere with the moving system reaching the ultimate deflection which it is desired to attain. A brake, while checking oscillations, would prevent a coil or needle from reaching the point intended. A true damper simply interferes with oscillations, but its resistance to motion disappears the instant it stops moving. In electro-magnetic damping a sheet of metal, usually of copper or aluminum, is placed in close proximity to a permanent magnet. The moving system causes relative motion between these two members. Whenever such motion takes place between a mass of metal and a source of magnetic lines of force, the lines are cut by the metal and electrical currents circulating in whirling eddies are induced therein. These currents set up magnetic poles in the metal which reach out toward the poles of the permanent magnet and by their reaction oppose the motion which induces them. The damping is very sharp and oscillations may be almost entirely prevented. This system is frequently employed in moving coil galvanometers. Thus, in Fig. 208, the coil *C* is wound on a small rectangular form of copper. This form constitutes a short-circuited coil of one convolution, in which powerful currents are induced by the oscillations. The reaction of these currents tends to quickly check the oscillations. This copper form is entirely separate from the coil *C*, which carries the current from without and which is insulated from, though wound upon, the short-circuited form.

Galvanometer Shunts

Instruments of the D'Arsonval class can carry only very minute currents, the actual currents being limited by the carrying capacity of the delicate suspending wire of the coil, *B*, Fig. 208. To increase the range of the instrument it is customary to employ a shunt. The principle of galvanometer shunts is illustrated in Fig. 210. Suppose a current of one ampere is passing through a line which includes a galvanometer, *G*. Let the maximum current which this galvanometer can carry be $\frac{1}{10}$ of an ampere. To conduct one ampere it will be neces-

sary to shunt the galvanometer with a circuit, S, capable of carrying $\frac{9}{10}$ of an ampere. As currents divide in branch circuits inversely as the resistance of the branches, the resistance of the shunt, S, must be one ohm if the resistance of the galvanometer is nine ohms. This will cause the one ampere in the main line to divide between the galvanometer and its shunt in the ratio of one to nine if the resistances are in the ratio of nine to one. If the deflection of the galvanometer is five divisions, when it is receiving $\frac{1}{10}$ ampere, assuming that the deflections are proportional to the current, the main line current may be calculated by multiplying the deflection by 10.

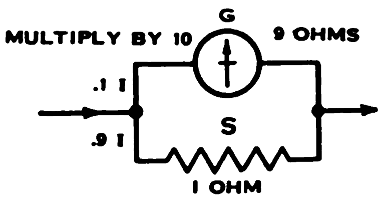


Fig. 210

Thus, 10 times 5 equals 50 divisions. This number, 10, is called the multiplying power of the shunt. When the deflection is multiplied by 10 the product does not indicate the current in the galvanometer nor the current in the shunt, but it is an indication of the entire current in the main line. To find the required resistance of a shunt to bring about any desired multiplying power, the resistance of the galvanometer in question must be divided by the desired multiplying power of the shunt, minus one.

$$\frac{\text{Resistance of galvanometer}}{\text{Multiplying power of shunt, } - 1} = \text{Resistance of shunt.}$$

Thus, assuming a galvanometer with a resistance of 180 ohms, if it is desired to provide it with a shunt which will have a multiplying power of 10, the resistance may be found by applying the formula:

$$Rs = \frac{Rg}{(m - 1)} = \frac{180}{10 - 1} = 20 \text{ ohms.}$$

To avoid the necessity of having a specially calibrated shunt to go with every galvanometer, the Ayrton Universal Shunt has been designed. This device may be used interchangeably with any galvanometer. Moreover, it is not necessary to know either the resistance of the galvanometer or the resistance of the shunt.

As has already been pointed out, the current in a galvanometer may be reduced by having resistance in shunt with it. The current may also be reduced by putting resistance in series with the instrument. The Ayrton shunt employs both schemes. To use this shunt, however, with the customary multiplying powers, it is necessary for any given series of operations, that the

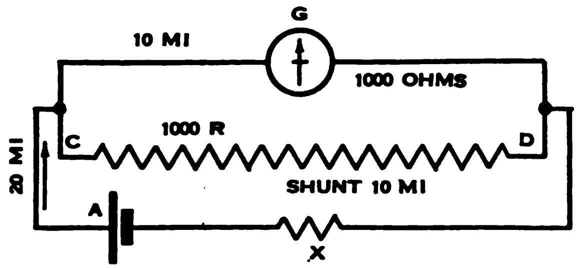


Fig. 211

galvanometer be normally shunted by the entire resistance, as in Fig. 211.

In this case, suppose the galvanometer to have a resistance of 1,000 ohms, while the shunt also has a resistance of 1,000 ohms. If a current of 20 milamperes enters this circuit at the point *A*,

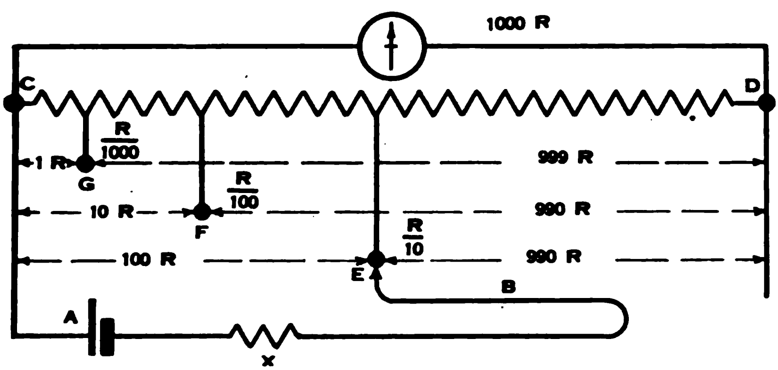


Fig. 212

it will divide equally through the galvanometer and its shunt, each receiving 10 milamperes. Now disconnect the wire *B*, Fig. 212, from the wire *D* and connect it at a point *E*, which, measured from *C*, is 0.1 of the total resistance of the shunt, *C-D*,

namely, 100 ohms. The actual connections will now be as in Fig. 213.

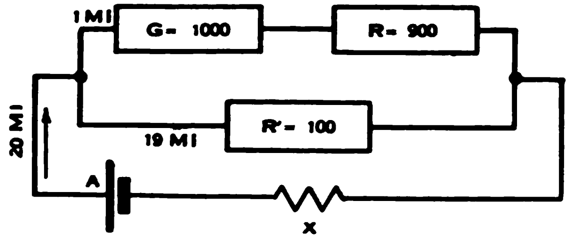


Fig. 213

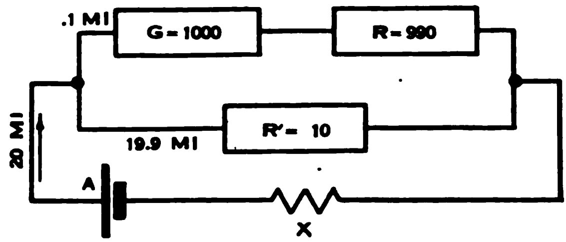


Fig. 214

Now 900 ohms is in series with the galvanometer, while 100 ohms is in shunt with both. The resistance of G plus R is 1,900 ohms and the resistance of the shunt is 100 ohms.

$$1{,}000 + 900 = 1{,}900 \text{ in } G \text{ and } R \quad 100 = R'$$

The relative conductivity of the two branches may be expressed as follows:

$$\frac{1}{1{,}900} + \frac{1}{100} = \frac{1}{1{,}900} + \frac{19}{1{,}900} = \frac{20}{1{,}900}.$$

Each branch will receive a portion of current inversely proportional to its resistance. Assuming the same current as before, the galvanometer and resistance in series with it will receive

$$\frac{1}{20} \text{ of 20 milamperes } = 1 \text{ milampere in } G \text{ and } R,$$

while the shunt will receive,

$$\frac{19}{20} \text{ of 20 milamperes } = 19 \text{ milamperes in } R'.$$

The combined amperes in G-R, and R' will therefore be 19+ 1= 20 milamperes. It is evident that the galvanometer now

receives 1 milampere while in Fig. 211 it received 10 milamperes. The multiplying power of the shunt in this position is therefore 10.

Now move wire B from the point E, Fig. 212, to the point F, where the resistance of C-F is 0.01 of the total resistance of C-D, namely, 10 ohms. The actual connections will then be as in Fig. 214.

The galvanometer is now in series with 990 ohms while 10 ohms is in shunt with both.

$$1{,}000 + 990 = 1{,}990 \text{ in } G \text{ and } R. \quad 10 = R'$$

The relative conductivities will be

$$\frac{1}{1{,}990} + \frac{1}{10} = \frac{1}{1{,}990} + \frac{199}{1{,}990} = \frac{200}{1{,}990}.$$

Assuming the same current as before, the division will be as follows: The galvanometer and resistance in series with it will receive

$$\frac{1}{200} \text{ of 20 milamperes } = 0.1 \text{ milampere in } G \text{ and } R,$$

while the shunt will receive,

$$\frac{199}{200} \text{ of 20 milamperes } = 19.9 \text{ milamperes in } R',$$

the two being equal to 20 milamperes, in the main circuit.

The galvanometer now receives 0.1 of 1 milampere, which is 0.01 of the current which it received in Fig. 211. The multiplying power of the shunt in this position is now 100.

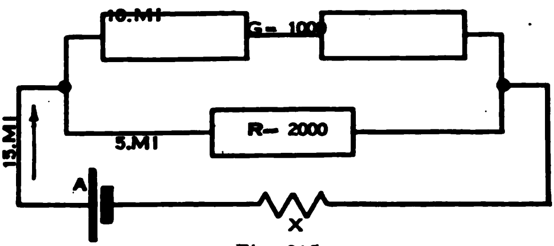


Fig. 215

It will be evident that by moving the wire B to the point G, the arrangement of the shunt and series resistances would be such as to give a multiplying power of 1,000.

Next, suppose the galvanometer to be shunted by 2,000 ohms as in Fig. 215, and that 15 milamperes enters the circuit from the

battery at A. The current will divide inversely as the resistances, 10 milamperes passing through the galvanometer while 5 milamperes passes through the shunt.

Next, suppose the wire B to be disconnected from the point D and moved to the point E, Fig. 216, where the resistance of

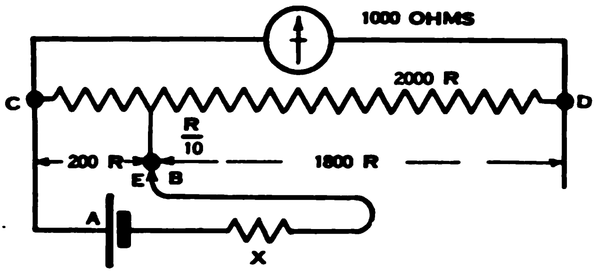


FIG 216.

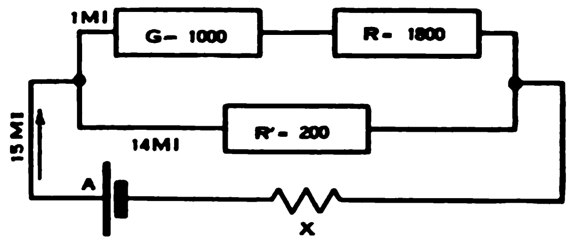


FIG. 217.

C-E is 0.1 of the total resistance of C-D. The actual connections will then be as shown in Fig. 217.

$$1{,}000 + 1{,}800 = 2{,}800 \text{ in } G \text{ and } R. \quad 200 = R'$$

The relative conductivities are:

$$\frac{1}{2800} + \frac{1}{200} = \frac{1}{2800} + \frac{14}{2800} = \frac{15}{2800}.$$

Assuming the same current, of 15 milamperes, as before, the galvanometer and resistance in series with it will receive

$$\frac{1}{15} \text{ of 15 milamperes} = 1 \text{ milampere in } G \text{ and } R.$$

While the shunt will get:

$$\frac{14}{15} \text{ of 15 milamperes} = 14 \text{ milamperes in } R'.$$

1 milampere in G and R + 14 milamperes in R' = 15 milamperes in main circuit.

The galvanometer now receives 1 milampere of current. This is 0.1 of the current which it received in Fig. 215. The multiplying power of the shunt is now 10.

The galvanometer therefore receives the same percentage of the total current in the main circuit, when the total resistance of the shunt is 2,000 **ohms** with the wire B connected at E, Fig. 216, as it does when the total resistance of the shunt is 1,000 **ohms** as in Fig. 212.

It will be observed that it is immaterial what the resistance of the shunt R is, as a whole, compared with the resistance of the galvanometer (either or both of which may therefore be unknown) for, if **any** current, I, flows through the galvanometer when the entire resistance is in shunt with the same, it will be:

$$\frac{I}{10}, \frac{I}{100} \text{ and } \frac{I}{1000} \text{ milamperes, respectively,}$$

when the wire B is touched at E, F and G, if the resistance of these taps from C is:

$$\frac{R}{10}, \frac{R}{100} \text{ and } \frac{R}{1000} \text{ ohms.}$$

The corresponding multiplying power of the shunt in the different cases will be 10, 100 and 1,000. This assumes that the current in the main circuit is the same in every case.

Fig. 218 is a diagram of the connections internally for a standard form of Ayrton Universal Shunt. The slider gives the mul-

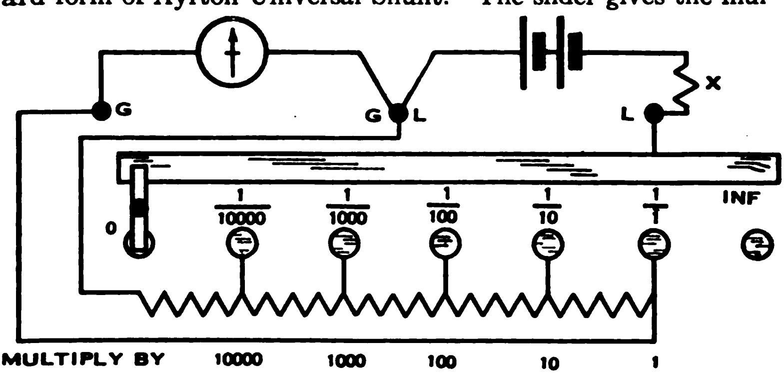


FIG. 218

tiplying powers indicated when on any particular contact point. When the slider is on the INF (infinity) point the circuit is open.

From the foregoing discussion it must be evident that the various multiplying powers obtained by the shunt all relate to the deflection which would be obtained on the galvanometer when the slider is on the contact which gives a multiplying power of one. That is to say, the shunt must be used with a multiplying power of one, in any operation which subsequently requires a shifting to a higher multiplying power.

The constant of a galvanometer is the amount of current required to produce a deflection of one scale division.

If I = current in amperes.
D = deflection in scale divisions.
K = galvanometer constant.

Then

$$K = \frac{I}{D} \qquad D = \frac{I}{K} \qquad I = KD.$$

To show the application of this formula consider the following example: What is the constant of the galvanometer if a deflection of 200 divisions is obtained by sending a current of 0.001 of an ampere through it? Assume that the deflections are proportional to the current. Applying the above formula:

$$K = \frac{I}{D} = \frac{0.001}{200} = 0.000005 (K).$$

The **sensitivity** of a galvanometer is sometimes defined as the number of ohms which, placed in series therewith, will permit of a deflection of one scale division when one volt is applied to the circuit.

SECTION VII — CHAPTER II

INSTRUMENTS AND MEASUREMENTS

TYPES OF GALVANOMETERS

1. Explain the construction of the Thomson mirror galvanometer. To what class does it belong? What is the method of control and what is the method of observation? Is it a long-coil or a short-coil instrument?

2. Explain the construction of the D'Arsonval galvanometer. What is the method of control? To what class does it belong? What is the method of observation? Is it a long-coil or a short-coil instrument?

3. Explain the construction of the Ayrton-Mather galvanometer. Wherein does it differ from the D'Arsonval instrument?

4. In what three ways may the moving member of a galvanometer be damped?

5. Explain the construction of some good form of air damper.

6. Explain the principle of electro-magnetic damping. In what instrument is this method used?

7. What is the object of a galvanometer shunt?

8. Explain fully the principle involved in galvanometer shunts. What multiplying powers are customarily employed?

9. If a shunt is to have a multiplying power of ten, what must be its resistance compared with that of the galvanometer?

10. If a galvanometer has a resistance of 180 ohms, what must be the resistance of a shunt connected around it, which will give a multiplying power of ten?

11. Explain the principle of the Ayrton Universal shunt.

12. A deflection of 125 divisions is caused by sending .001 of an ampere through a reflecting galvanometer. If the deflections are proportional to the current, what is the galvanometer constant?

13. A reflecting galvanometer and resistance box in a series have a total resistance of 100,000 ohms. One volt pressure causes a deflection of 80 divisions on the galvanometer scale. If the deflections are proportional to the current, what is the constant of the galvanometer?

14. A certain current causes a deflection of 80 divisions on a galvanometer scale. If the constant of the galvanometer is .0001, what is the current?

15. The total resistance of a circuit containing a galvanometer is 10,000 ohms. The constant of the galvanometer is .0001. If the galvanometer is deflected 10 divisions what pressure is impressed upon the terminals of the circuit?

16. A galvanometer has a resistance of 143.55 ohms; it is desired to shunt it so that only .01 of the total current to be measured will pass through it. What must be the resistance of the shunt?

17. A galvanometer, in which the deflections are proportional to the current, is deflected 100 scale divisions by 1 milampere. What is the strength of a current which causes a deflection of 150 divisions when the galvanometer is shunted by a 1/99th shunt?

18. A galvanometer having a constant of .0005 of an ampere shows a reading of 200 divisions when shunted by a 1/99th shunt box. What current is flowing?

19. A deflection of 20 divisions is caused by sending .01 ampere through a circuit leading to a galvanometer which is shunted by a 1/9 box. If the deflections are proportional to the current what is the galvanometer constant?

20. A galvanometer whose resistance is 21 ohms gives a deflection of 40 divisions with a current of 2 amperes; what will be the resistance of the shunt that must be used to cause 16 amperes to give the same deflection?

21. A galvanometer has a resistance of 45 ohms; it shows 40 scale divisions deflection when 0.5 of an ampere flows through it. If the deflections are directly proportional to the current, what must be the resistance of a shunt around this galvanometer which will bring about a deflection of 20 divisions when 1.75 amperes is passing through the main line?

INSTRUMENTS AND MEASUREMENTS

VOLTMETERS AND AMMETERS

While galvanometers may be used to measure the strength of a current, these instruments are generally provided with uniformly divided scales; and in order to estimate the amperes passing, it is necessary to multiply the deflection in any instance, by the constant for that particular instrument. Thus, if an instrument possesses a constant of 0.05 and a certain current produces a deflection of 40 scale divisions, according to the formula, $I = KD$; 0.05 times 40 equals 2 amperes. Obviously, such an indirect method is cumbersome for commercial purposes. Modern instruments are therefore calibrated to read directly the current in the instruments or the voltage applied at the terminals of the instrument to bring about a certain current therein.

An **ammeter** corresponds to a short coil galvanometer calibrated to read the current directly in amperes. It has a very

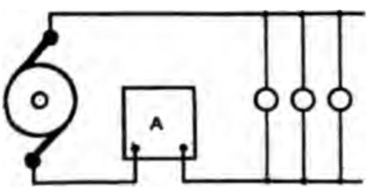


FIG. 219.

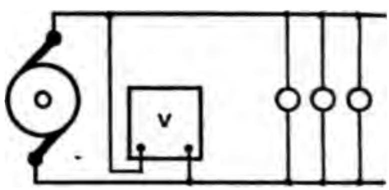


FIG. 220.

low resistance, usually a fraction of an ohm, and is placed in series with the circuit, the current strength of which it is desired to measure, Fig. 219. In this position it acts like a water meter or a gas meter and passes the entire volume of the current.

A **voltmeter** corresponds to a long coil galvanometer calibrated to read the potential difference at its terminals. It is connected across the line between the two wires of the circuit, Fig. 220, the potential difference of which it is desired to measure. It is of high resistance, generally several thousand ohms. It indicates the electro-motive-force indirectly. That is, it passes a current due to the pressure applied. Instead, however, of marking the value of the current in amperes on the scale, it is customary to mark the value of the voltage applied at its terminals,

which of course corresponds to a certain current in the instrument, the current, however, being unknown. It is thus possible to calibrate an instrument so that its scale will show the actual current in it, in which case it is called an ammeter, or it may be calibrated to show the potential difference at its terminals, in which case it is called a voltmeter.

Edison Pendulum Ammeter.—One of the earliest forms of direct reading current measuring instruments was the pendulum ammeter, Fig. 221. This instrument was devised by Edison, and consists of a so'enoid, *A*, a soft iron core, *B*, pivoted at *C*, with a counter-weight, *D*, to hold the core at the entrance to the solenoid. When a current enters the instrument at the binding posts *E-F*, the solenoid is energized and magnetizes the core, *B*, by induction. The core is drawn into the coil, *A*, in accordance with the law that magnetic circuits tend to arrange themselves so as to increase the magnetic flux within the embrace of any coil. This carries the index, *G*, across the scale. The instrument has no damping mechanism and the deflections are not proportional to the current. The scale must therefore be calibrated with every increase in current to correspond with a standard instrument in the same circuit.

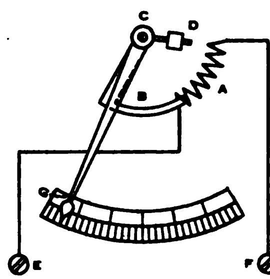


FIG. 221.

Battery Gauge.—This type of instrument is found in use today chiefly in the form of small watch-case instruments known as battery gauges, Fig. 222. A phosphor-bronze spring, *S*, replaces the counter-weight, *D*, of Fig. 221, enabling the instrument to be used in any position. If the coil, *E*, is of coarse wire it is adapted for use as an ammeter. Battery gauges are built with coils of this sort for detecting momentarily the short-circuit current from dry cells. They usually have a range up to about 30 amperes. If the coil is of fine wire, the scale may be calibrated in volts. Instruments are so constructed with a range of 0-10 volts. By winding two coils, one coarse, *A-B*, and one fine, *A-C*, upon the same form and connecting them to separate binding posts, the instrument may be provided with two scales, using the fine wire for a voltmeter, and the coarse wire coil for an ammeter. The soft iron core, *D*,

in this type of instrument is generally tapered. Thus, while it extends the entire length of the coil to begin with, it is narrower at the end E than at the point D. The core, therefore, moves in an effort to increase the amount of iron within the coil, thereby increasing the permeability of the path and increasing the flux.

Weston Voltmeter.—A most widely used type of commercial voltmeter is the Weston instrument. This is built on the principle of the D'Arsonval or moving coil galvanometer. It consists of a

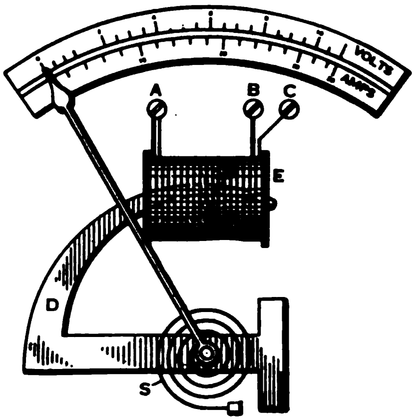


FIG. 222.

powerful permanent magnet, M-M, Fig. 223, with a core of soft iron mounted between the poles. Surrounding this core and supported in sapphire jewels is a small coil, C. Current is admitted to and taken from the coil by two phosphor-bronze spiral springs, D-D, one above and one below the coil, wound in opposite directions, Fig. 224. This coil is placed at an angle in the magnetic field. When current is introduced it tends to rotate in an effort to include the flux from the permanent magnet, M-M, within its embrace. This motion is opposed by the phosphor-bronze springs. Because of the uniform field in which the coil moves throughout its entire range, the deflections in this instrument are proportional to the current. This insures a uniformly divided scale. Most galvanometers do not have scales in which the deflections are proportional to the current. The resistance of the coil C varies according to the type of instrument, between 1 and 80 ohms. Because of the intense field in which the coil

moves, very little current is required to produce a deflection. In fact, with an instrument having a coil resistance of about 2

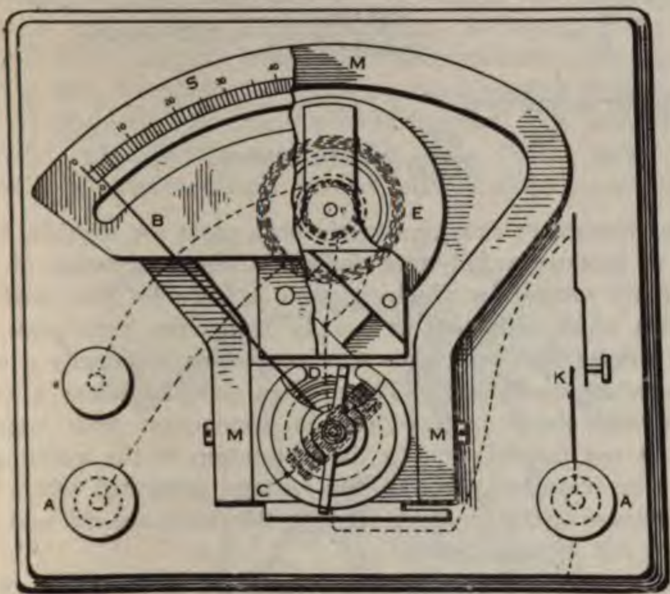


FIG. 223.

ohms, 0.05 volt will produce a full scale deflection. The current required may be found as follows:

$$\frac{E}{R} = I \quad \frac{0.05}{2} = 0.025 \text{ amperes.}$$

A single cell of dry battery furnishes 1.5 volts. Such a source would furnish thirty times the voltage required to produce a full scale deflection. To adapt it for higher voltages, resistance must be connected in series with the coil. The commercial form of voltmeter uses such a resistance coil, *E*, Fig. 223, connected in series with the moving coil. This resistance is approximately equal to 100 ohms per volt of scale deflection. Thus, a 150-volt instrument would have a resistance of 150 × 100 =

FIG. 224.—Construction of moving coil in Weston voltmeter.

15,000 ohms. A 300-volt instrument would have $300 \times 100 =$ 30,000 ohms. The current which the instrument would receive in each case would be the same. Thus, in the first case,

$$\frac{E}{R} = I \qquad \frac{150 \text{ (volts)}}{15{,}000 \text{ (ohms)}} = 0.01 \text{ ampere,}$$

and in the second case,

$$\frac{300}{30{,}000} = 0.01 \text{ ampere.}$$

The instrument thus receives in both cases the requisite current to produce a full scale deflection when subjected to the maximum voltage for which the scale is laid off. The material for this series resistance is usually manganin, constantin, or some similar high resistance wire possessing practically a zero temperature coefficient. These wires should possess a very low thermo-electro-motive-force, in connection with copper. Were it not for this quality the calibration of the instrument might be disturbed, due to the voltage generated when the temperature of the juncture between the resistance coil and the moving coil increased.

The magnetic circuit in this instrument is especially good. The magnets are well saturated and seasoned. There is very little tendency, therefore, for the magnetism to change. It is important that there shall be no alteration in the value of the permanent magnetic field, otherwise the accuracy of the instrument would be impaired.

These instruments are affected by stray magnetic fields from any near-by conductors carrying large currents. To shield them so that their indications may be relied upon at all times, the entire instrument is encased in a cast iron box. This renders the instrument immune to all magnetic fields except those produced within the instrument itself.

This type of instrument is applicable for direct current only. An alternating current would tend to turn the moving coil first one way and then the other. With commercial frequencies there would be 120 of these alternating impulses per second. The coil would simply tremble and not move in either direction and the alternating magnetic forces would disturb the permanent magnetic field. No instrument containing permanent magnets

should be used on alternating current circuits unless the magnets are used for damping purposes only.

Magnetic Vane Instruments.—A simple and widely used form of alternating current instrument is shown in Fig. 225. This is of the magnetic vane type. Like the instrument pictured in Fig. 221, it contains no permanent magnets but depends simply on magnetic induction for its operation. The principle can best be understood by studying Fig. 226. Here a coil, *C*, surrounds two pieces of soft iron, *A* and *B*, both extending the

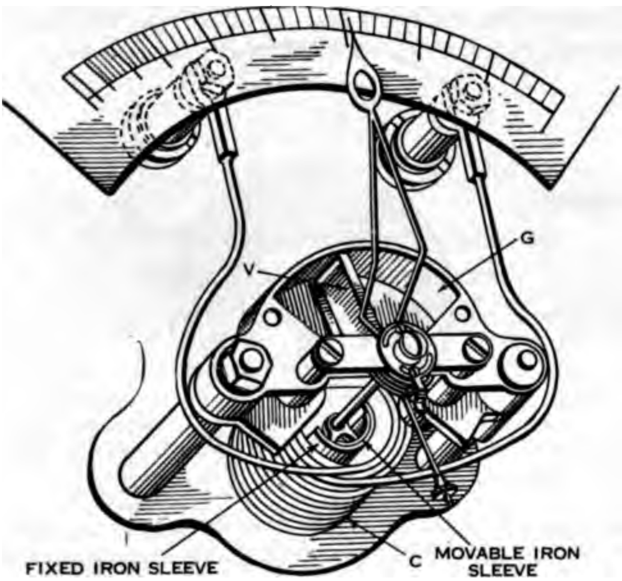


Fig. 225.

length of the coil, parallel to its axis. *A* is stationary and attached to the coil. *B* is free to rotate about the central axis of the coil with the shaft to which it is attached. When a current circulates, the two ends of *A* and *B* nearest the observer are magnetized with like poles, while the two ends farthest away are magnetized with similar poles, opposite in sign to those at the front of the coil. The Weston instrument shown in Fig. 225 embodies this principle although the disposition of the iron in the magnetic circuit is somewhat different. In all instruments of this type, however, there is a moving member which tends to alter its position within the coil so as to increase the magnetic

flux. The coil, *C*, is stationary. If wound with coarse wire the instrument is calibrated as an ammeter. If wound with fine wire it is used as a voltmeter. As no permanent magnets are used in this instrument it is not practical to use electro-magnetic damping. The instrument is most effectively damped, however, by a highly efficient air damper. This consists of a curved aluminum box, *G*, in which there moves a snugly fitting aluminum vane, *V*, which barely clears the box on all sides. The box is fitted with a cover containing two holes which allow the air to be excluded just fast enough to insure effective damping. A spiral

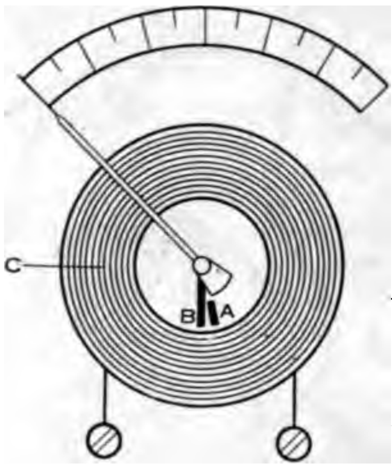


FIG. 226.—Magnetic vane instrument for either A.C. or D.C.

phosphor-bronze spring furnishes the control and an adjustment is provided to bring the index to zero on the scale. The instrument is adapted for either A. C. or D. C. Most instruments containing soft iron have to be specially calibrated if used on A. C. circuits. This is because of the hysteresis effect; that is, the lag in the magnetizing of the iron behind the application of the magnetizing force. Such instruments therefore tend to indicate low on alternating currents as compared with equal D. C. values. This is because the magnetism does not have time to reach its maximum value before the current reverses, with A. C. on the line. In the Weston instrument, there is a very minute amount of iron of a high degree of purity employed.

This reduces the hysteresis loss to a negligible quantity and the instrument indicates practically the same on both A. C. and D.C. The instrument is not often used on D. C., however, because it is not as efficient nor as accurate as the permanent magnet type. In the type shown in Fig. 223, the powerful permanent magnetic field acts as a fulcrum on which the moving coil exerts a great leverage with a very minute current. No such field exists in the magnetic vane type in Fig. 225, but the current itself must develop the magnetism which brings about the reaction between the moving and stationary members. The result is that a 300 volt instrument of the latter type requires approximately six times the power to produce a full scale deflection of that required for the former.

SECTION VII CHAPTER III

INSTRUMENTS AND MEASUREMENTS

VOLTMETERS AND AMMETERS

1. Explain the construction of an ammeter. To what type of galvanometer does it correspond? How should it be connected in circuit? Sketch.
2. Explain the construction of a voltmeter. To what type of galvanometer does it correspond? How should it be connected in circuit? Sketch.
3. Explain the construction of the Edison pendulum ammeter.
4. Explain the construction of a battery gauge. How is it wound when designed as a voltmeter? How is it wound as an ammeter? How is it designed as a combined ammeter and voltmeter?
5. Explain the construction of the Weston direct current voltmeter. Are the scale divisions proportional to the current in it? Why?
6. How is the Weston voltmeter movement adapted for use on 150- and 300-volt circuits?
7. What are the relative currents absorbed by a Weston 150-volt voltmeter and a 300-volt voltmeter when each is showing a full scale deflection?
8. Explain the construction of the Weston Model 155 magnetic vane instrument. Upon what principle does it operate? For what kind of current is it adapted? May it be used for any other kind of current?
9. What are the relative advantages of the Weston Model 45 and the Weston Model 155 voltmeters? What are the relative number of watts which they absorb? Why should not one always be used in place of the other?

INSTRUMENTS AND MEASUREMENTS

SHUNT AMMETERS

Ammeters which are placed in series with the line and pass the entire current consume considerable power, and it is often inconvenient to carry very large currents into the instruments. The difficulty of making connections, the resistance offered, the energy to be dissipated, all make such instruments bulky and inefficient.

Dr. Weston was the first to apply the principle of the galvanometer shunt to the measurement of large currents by means of a sensitive D'Arsonval type of instrument. Using practically the same movement that he employed for a voltmeter, he constructed

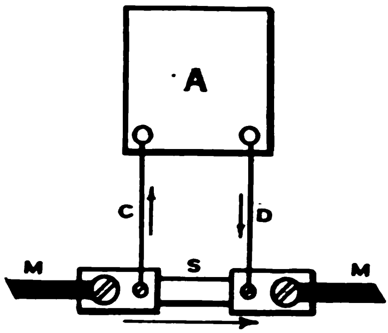


FIG. 227.

an ammeter. The connections for this instrument are shown in Fig. 227. Here the main line current is passed through a carefully calibrated shunt strap, S. The ammeter, A, is really a sensitive millivoltmeter, which measures the fall in potential across the shunt strap. The shunt straps are made with massive terminals and with the resistance material laminated so as to radiate the heat readily, see Fig. 228. The material from which the shunt is made has practically a zero temperature coefficient. These shunts are usually calibrated so that the fall in potential across their terminals will be 50 millivolts when carrying their full rated current. The instrument is connected to the shunt strap and when the full rated current is passing, the strap is

adjusted to bring about a full scale deflection. Shunts of various ranges may be employed with the same instrument. Thus, let Fig. 227 represent a shunt with a resistance of 0.0005 ohm. 100 amperes through this shunt will bring about a drop of potential of 0.05 volt. This pressure will cause a full scale deflection in a standard instrument of this type. If the instrument has 100 scale divisions, every division represents one ampere of current in the main line. Now substitute for this shunt, another shunt having ten times the resistance, or 0.005 ohm. In this instrument 10 amperes will produce a drop in potential of 0.05 volt and bring about a full scale deflection of the indicating instrument. The range of the instrument is now 10 amperes instead of 100 and every scale division represents 0.1 of an ampere. Next

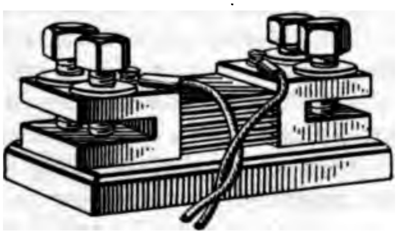


FIG. 228.

replace this shunt with another having a resistance of 0.05 of an ohm. One ampere will cause a drop in potential of 0.05 volt in such a shunt and produce a full scale deflection. Each scale division now corresponds to 0.01 of an ampere and the range of the instrument is one ampere. It will thus be seen that the **same millivoltmeter** may be used to indicate a **full scale deflection** with either **1 ampere, 10 amperes** or **100 amperes, depending upon the shunt** employed with it.

While it is true that in divided circuits each branch passes a portion of current inversely proportional to its resistance, and it is to be expected that a portion of the main line current will go through the instrument, while the remainder only goes through the shunt, as a matter of fact, the portion of current which the instrument takes is so minute that for all practical purposes it may be assumed that the entire main line current goes through the shunt strap. The instrument, therefore, simply has to measure the fall in potential across the strap.

While the principle of the shunt type of ammeter is the same as that employed with galvanometers and their shunts, no attempt need be made to compute the current in the shunt type of ammeter itself by using the formulas employed to determine the current in a galvanometer when shunted by a definite resistance. The actual resistance of the shunt for any ammeter is ascertained by a simple application of Ohm's Law as set forth in the preceding paragraph.

It is important that the lead wires, *C-D*, Fig. 227, employed in the calibration of an instrument with any shunt, should always be used with that shunt, for the fall in potential encountered due to the resistance of the wires enters into the deflection obtained on the instrument with a given current. If a high voltage was being employed, a small change in this resistance would make little difference, but on account of the fact that only 50 millivolts are used in the entire circuit, any alteration in the resistance of the leads would alter the deflection obtained with a given current in the shunt. The leads are usually about six feet long. They must never be lengthened or shortened after the instrument is once calibrated, for to do so would throw the instrument out of calibration.

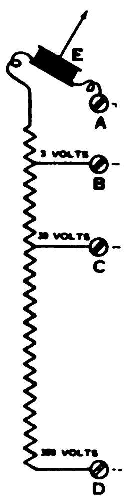


FIG. 229.

As has already been pointed out, the moving coil of an instrument of this type may be adapted for different voltage ranges by varying the resistance in series. Thus, suppose the total resistance between the positive and negative terminals of a voltmeter, Fig. 229, is 30,000 ohms. 300 volts applied to these terminals will produce a full scale deflection. If a tap is taken at the point *C*, where the resistance between *A* and *C* is $1/10$ of the resistance between *A* and *D*, then 30 volts applied to *A-C* will produce the same current in the moving coil *E* and produce a full scale deflection. Each division on the scale now has $1/10$ of the value that it had before. If another tap is taken at the point *B*, where the resistance from *A* to *B* is $1/100$ of the resistance from *A* to *D*, then 3 volts applied to *A* and *B* will produce a full scale deflection. The instrument then becomes a multi-scale voltmeter and is adapted for 3 volts, 30 volts or 300 volts, depending upon

whether binding post B, C or D is employed in connection with the common terminal A.

The range of a voltmeter may thus be indefinitely extended by the addition of resistance in series. The practical limit, however, is about 600 volts, due to difficulties in insulation. The range of such an instrument as an ammeter may be indefinitely extended by placing resistance in shunt with the instrument. The **higher** the resistance in **series** with the instrument, the greater its range as a **voltmeter.** The **lower** the resistance in **shunt** with the instrument the greater its range as an **ammeter.**

Shunt ammeters of the above type, therefore, do not have $\frac{1}{9}$ and $\frac{1}{99}$ shunts as with galvanometers. In fact, for practical measurements, it is not necessary to know either the resistance of the shunt or of the millivoltmeter used therewith. The two are placed in parallel and the instrument is calibrated by altering the resistance of the shunt strap until the desired current produces a sufficient drop to bring about a full scale deflection. As a matter of fact, the resistance of a 10-ampere shunt strap is about $\frac{1}{400}$ of the resistance of the millivoltmeter used with it.

If a sensitive instrument of the above mentioned type has fifty scale divisions, and requires 50 millivolts to bring about a full scale deflection, then it is a direct reading millivoltmeter, in which each scale division corresponds to one millivolt. Now, if such an instrument also possesses a resistance of just one ohm, then it becomes at the same time a direct reading millammeter, because 50 millivolts will cause just 50 milamperes to flow through a resistance of one ohm. Such instruments are occasionally found. Usually, however, the scale of a millivoltmeter does not have fifty divisions, but more likely one hundred. Likewise, the scale of a milammeter is not direct reading. It is therefore necessary to employ a constant to calculate the actual millivolts or milamperes in either case.

The constant of a millivoltmeter is the number by which the deflection must be multiplied in order to get the true millivolts. Thus, if an instrument has 100 scale divisions and a constant of 0.5, the millivolts are $D \times K = M.V.$ 100 times 0.5 equals 50 millivolts. The constant, 0.5, is therefore the number of millivolts required to produce a deflection of one scale division. This

corresponds very closely with the definition of a galvanometer constant.

The constant of a milammeter is the number by which the deflection must be multiplied to get the true milamperes. Thus if one milampere causes a deflection of five divisions, the constant, K, will be ascertained from the formula:

$$\frac{I}{D} = K = \frac{1}{5} = 0.2.$$

The actual power consumed by a millivolt meter movement is exceedingly small. In one type the resistance of the moving coil alone is 2 ohms. The pressure required to produce a full scale deflection is 0.05 volt. The instrument, therefore, receives 0.025 ampere. The actual power absorbed is thus only about 0.001 watt. A forceful illustration of the power required to actuate one of these instruments may be obtained when it is considered that the power consumed to light one 40-watt Mazda lamp would be sufficient to bring about a full scale deflection in 40,000 of these instruments simultaneously. When the moving coil is employed with a shunt strap, as an ammeter or with resistance in series as a voltmeter, the power consumed is considerably greater.

A comparison of the wattage required by the permanent magnet direct current, and magnetic vane alternating current type of instruments, to cause full scale deflections is given below:

Permanent Magnet Type, D. C.	Magnetic Vane Type, A. C.
10 Amp. Shunt and Millivolt = 0.5 Watts.	10 Amp. (series) = 1.3 Watts.
150 Volt Voltmeter (15,000 R) = 1.5 Watts.	125 Volt (1,630 R) = 10 Watts.
300 Volt Voltmeter (30,000 R) = 3.0 Watts.	250 Volt (3,784 R) = 16 Watts.

In practice the moving coil in the instrument used as a millivoltmeter for measurement of currents with a shunt strap is constructed differently from the coil in an instrument for use with resistance in series as a voltmeter. The resistance of the millivoltmeter coil is approximately 1.8 ohms, and has phosphor-

bronze springs of large cross-section and low resistance. The coil of an instrument intended for use as a 300-volt voltmeter has approximately 70 ohms resistance and phosphor-bronze springs of considerably smaller cross-section.

Thomson Inclined Coil Instruments.—An unusual form of ammeter manufactured by the General Electric Company is the Thomson inclined coil instrument. As its name indicates, the coil is inclined at an angle of about 45 degrees from the horizontal. Within the coil is placed a small disc of iron mounted on a vertical shaft also at an angle of 45 degrees. This disc normally stands with its surface parallel to the plane of the coil. When a current passes, the disc turns in an effort to place itself on edge in the coil, thus reducing the reluctance to magnetic lines. In so doing the index is rotated across the scale. It is often provided with a rather crude air damper, consisting of an aluminum vane, which travels under the dial. The voltmeter of this same type has the inclined disc replaced by a coil of fine wire connected in series with the stationary coil. This moving coil attempts to line its flux up with that of the stationary coil when voltage is applied at the terminals. These meters are used for alternating current measurements. If used for D. C. reverse readings must be taken to eliminate external field effects.

Electro-static Voltmeters.—For measuring A. C. voltages ranging above 1,100 it is customary to employ transformers, which reduce the voltage to about 110, which is applied to suitably designed voltmeters. This avoids the necessity of insulating the voltmeter itself for high voltages. A transformer can be more readily insulated for high voltage than an instrument with moving parts. For measuring high voltages above 11,000, electro-static voltmeters may be employed. A simple instrument of this type is illustrated in Fig. 230. Here stationary metal quadrants, Q-Q, are mounted in front of a similar pair placed a short distance behind them. Pivoted on an axis at the center is an aluminum vane, N-N, while a

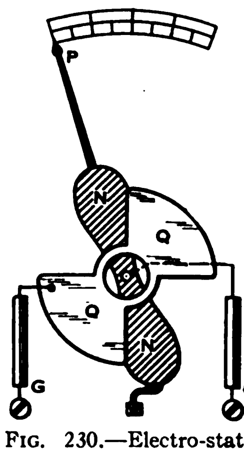


FIG. 230.—Electro-static voltmeter.

counter-weight, W, serves to keep the pointer at zero on the scale. The stationary quadrants are connected to one side of the line while the movable aluminum vane is connected to the other side of the circuit, the potential difference of which it is desired to measure. N-N and Q-Q are thus charged oppositely and attract each other. The force of attraction is proportional to the square of the potential difference applied. It will be noticed that this type of instrument takes no current whatever on D. C. and a very small current with A. C., depending solely for its operation on the attraction of oppositely charged conductors. To avoid the possibility of a high voltage system short-circuiting across the two members of this instrument, it is connected to the line in series with high resistance graphite members, G-G, which, while not interfering with the passage of charges into the instrument, will effectually bar any appreciable current. A commercial form of electro-static voltmeter for high voltages is shown in Fig 231. This instrument is built upon the principle of the attracted disc electrometer. Here a suspended aluminum disc, D, is hung from one end of a lever pivoted at C, and supported by a counter-weight, W. The movable disc is attracted by a stationary disc, F, which is mounted immediately beneath it. These two discs are connected to opposite sides of the line through suitable resistances to prevent short circuiting, as in the preceding instrument. The attraction between D and F is proportional to the square of the potential difference applied. The fact that the instrument is used to measure alternating current potentials does not affect its operation, for when the polarity of the line reverses the charges in the two discs simultaneously reverse and the attraction remains unaltered.

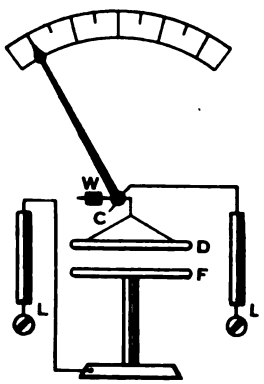


FIG. 231.—Attracted disc form of electro-static voltmeter.

Because of the fact that these instruments require practically no energy they are manufactured by some of the large companies for use on very low voltages where high efficiency is required. Each member consists of a large number of vanes in multiple.

SECTION VII CHAPTER IV

INSTRUMENTS AND MEASUREMENTS

SHUNT AMMETERS

1. Explain the construction of the Weston shunt ammeter. What does this instrument really measure? Sketch connections.

2. In practice, what is meant by a "1 ampere shunt?" What is meant by a 100 ampere shunt? Explain how various shunts may be used with the same instrument. If the above-mentioned instrument reads directly on its scale with the 100 ampere shunt in circuit, how many scale divisions will be produced when the 10 ampere shunt is substituted with one ampere passing in the line?

3. How may a voltmeter be constructed so as to have several different scale readings?

4. Explain the construction of millivoltmeters and milammeters.

5. If a millivoltmeter has 100 scale divisions and the constant is 0.6 what will be the pressure in millivolts required to produce a full scale deflection?

6. If full scale deflection of 200 divisions is obtained by the application of 100 millivolts to the terminals of an instrument, what is the constant?

7. If a millivoltmeter with a constant of 0.6 has 60 millivolts applied to its terminals to produce a deflection of 100 scale divisions, what is the value of each division?

8. A milammeter has a constant of 0.2 and its scale has 50 divisions. How many milamperes are required to produce a full scale deflection?

9. Thirty milamperes passing through an instrument produce a full scale deflection of 100 divisions. What is the constant of the instrument?

10. A milammeter with a constant of 0.2 produces a full scale deflection of 75 divisions when passing 15 milamperes. What is the value of one scale division?

11. Explain the construction of the electrostatic voltmeter. What precaution must be taken to prevent short-circuiting the line? For what kind of circuits is this instrument adapted?

12. Explain the construction of the Thomson inclined coil ammeter. Explain the construction of the Thomson inclined coil voltmeter. Wherein do they differ?

13. If the moving coil of a Weston permanent magnet instrument has a resistance of 2 ohms and requires 0.05 volts to produce a full scale deflection, what must be the resistance of a shunt strap used with it as an ammeter to bring about a full scale deflection when 25 amperes pass to line?

14. If the moving coil of a Weston permanent magnet instrument has a resistance of 70 ohms and requires 01. ampere to produce a full scale deflection, what resistance must be placed in series with the coil in order that 150 volts shall produce a full scale deflection?

INSTRUMENTS AND MEASUREMENTS

INDICATING WATTMETERS AND WATT-HOUR METERS

A wattmeter is an instrument for indicating the instantaneous value of the power in an electrical circuit. It consists of two members; First, a coil, *A*, Fig. 232, of coarse wire, in series with the line, the strength of its field being proportional to the amperes passing. Second, a coil, *B*, of fine wire, connected in shunt with the line, the strength of its field being proportional to the

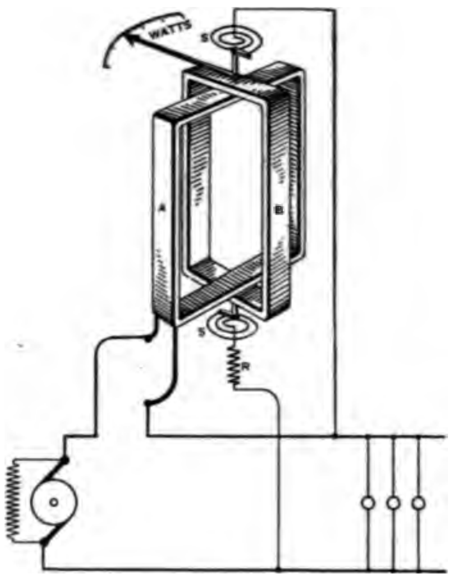


FIG. 232.—Principle of indicating wattmeter showing current coil *A* in series with the line and potential coil *B* in shunt with the line.

potential difference of the circuit. It will be remembered that in a dynamometer the force with which the moving member tended to turn was not due to the sum of the strengths of the separate fields in the two coils, but to their product. Now, if the field of *A* is proportional to the current in the line and the field of *B* is proportional to the voltage of the line, and if these two coils

are so mounted that they may interact on each other, the resulting tendency of the coils to turn is proportional to the product of their field strengths. Now the product of the volts and the amperes is the watts. Hence, such an instrument will give a deflection which is proportional to the power in watts supplied to the circuit in which it is connected. The moving coil, *B*, is mounted in jewel supports as is customary with a voltmeter. Current is admitted by means of phosphor-bronze spiral springs, *S-S*, as before. An extra resistance, *R*, is placed in series as in a voltmeter. The stationary coil, *A*, is of sufficient cross-section to carry the entire current for the circuit in which it is connected.

Weston Wattmeter.—Fig. 233 shows the outside appearance of a wattmeter built on this plan. *E-E* are the terminals of the potential winding, while *C-C* are the terminals of the current winding. *B* represents a button which operates a switch to close the potential circuit.

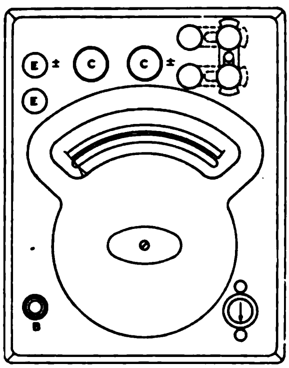


Fig. 233.—General appearance of Weston wattmeter.

A schematic diagram of the electric circuits including a compensating arrangement is shown in Fig. 234. Here the current coil, *D*, is shown connected in series with the line. The potential circuit is taken from the line at *E* and passes through a compensating coil, *K*. Thence it passes through the potential coil, *L*, and the extra resistance, *R*, and from the binding post *B* to the other side of the line *G*. The object of the compensating coil is to make the instrument indicate the true power absorbed by the load at *H*. It will be observed that the current entering by the line *F* is more than the current required by the load *H*, by the amount which leaves the line at the point *E* and traverses the compensating coil and potential winding. This current should not be charged up to the load. Therefore, the compensating winding has the same number of convolutions as the series winding, and the current for the compensating coil *K* is led **backward** through this winding in the opposite direction to that of the current in the series winding. Therefore, whatever extra magnetizing effect was produced in

the coil D due to the current for the potential circuit, is exactly counter-balanced or neutralized by leading the same amount of current, in the opposite direction through the compensating winding, on its way to the potential circuit. This leaves an amount due to the current required by the load, H, solely, effective in the series winding, while the potential applied to that load is correctly measured by the potential circuit connected at E-G. If the output of a generator or transformer is to be measured, the compensating coil is not needed, and an independent binding post, "IND," is therefore provided for such outside connection. Under such circumstances the potential circuit is connected between "IND" and B. In this case the resistance of the potential circuit is kept at its former value by passing the current through an added resistance coil, S, equal in amount to the resistance of the compensating coil K.

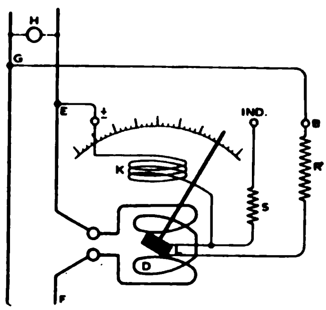


FIG. 234.—Circuits through Weston wattmeter.

Thomson Inclined Coil Wattmeter.—The Thomson inclined coil instrument may also be designed as a wattmeter. The inclined coil used in the instrument as an ammeter remains. The moving disc of soft iron, however, is replaced by a fine wire moving coil, free to rotate upon a perpendicular axis. The tendency of these two coils to line up is proportional to the product of their separate strengths and the deflection across the scale measures the watts. The instrument is provided with an air damper of aluminum.

Thomson Watt-hour Meter.—For registering the power and the time in a circuit, a motor type of meter is used. The earliest instrument of this sort was the Thomson watt-hour meter. The principle is illustrated in Fig. 235, where two stationary field coils, F-F, are connected in series with each other and in series with the line. The strength of the field is proportional to the current passing. Mounted upon a vertical shaft between these two coils is an armature, A, consisting of several coils of fine wire, wound like a motor armature and connected to

a silver commutator, C, on which rest two silver faced brushes. This insures a minumim of variation in resistance due to the sliding contacts. An extra series resistance, R, the armature winding, A, and a shunt field coil, S, constitute the potential circuit, the terminals being connected in parallel with the line. The magneto-motive-force of the armature A is at right-angles to the field produced by the field coils, F-F. The reaction of the current in the coils, A, causes this member to rotate as in an ordinary direct-current motor. As the flux due to the field coils, F-F, is proportional to the current in the line and the strength of the armature A is proportional to the potential of the line, the turning effort is proportional to the product of these two forces, or the watts, as in the indicating instrument previously described. To prevent the weakest current from rotating the armature as fast as a stronger current, the motor must be provided with a load. This is arranged for by attaching to the vertical shaft a copper or aluminum disc, D, which is rotated between the poles of two powerful permanent magnets, MM. These are termed the **drag magnets,** because they furnish the load. As the disc moves between these poles, which, however, it does not touch, it cuts the lines of force of the permanent magnets, thereby causing eddy currents to flow within itself. The reaction of the magnetic fields produced by these eddy currents upon the poles of the drag magnets opposes the motion of the disc, as in the case of any electro-magnetic damper. This load imposed on the armature corresponds to the control afforded by the spiral spring in an indicating instrument. Now, the retarding effect of the drag magnet system is exactly proportional to the increase in speed. Therefore, if the increase in driving torque is proportional to the power supplied through the instrument, the speed of the armature will always be in exact proportion to the power, thus registering the product of the watts and time correctly on the dial. If, with a certain current passing

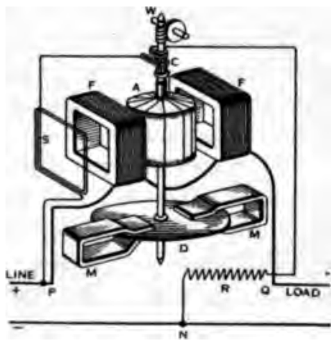


FIG. 235.—Circuits through watt-hour meter showing current coils F-F in series with line and potential circuit through shunt coil S, armature A, and card resistance R in shunt with the line.

and voltage applied, the armature revolves 60 revolutions per minute, doubling the current in the load would double the strength of the field coils *F-F*, and the armature would run 120 revolutions per minute, thus bringing about twice the total number of revolutions in a given time. If, on the other hand, the voltage applied to the line increased 10%, while the current was unaltered, the strength of the armature *A* would rise 10%, and the reaction between *A* and *F-F* would increase 10%, and the speed would go up 10%, thus bringing about 10% increase in the number of revolutions in a given time.

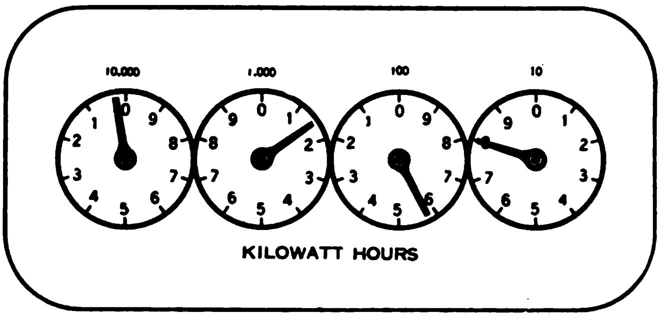
A worm gear *W* in the top of the shaft connects with a clock train, which thus mechanically sums up the product of the power and the time, the dial being calibrated to register the watthours. The shaft is mounted in sapphire jewels which form practically a frictionless support.

This meter has two adjustments, one for light load and one for full load. The full load adjustment is obtained by shifting the drag magnets, *M-M*, Fig. 235, toward the center, or toward the circumference of the disc. These magnets are made adjustable for this purpose. The instrument is loaded to its full capacity and its readings are compared with a standard instrument. If it reads too slow the magnets are moved toward the center of the disc. The rate of cutting lines of force is less here than near the circumference. The drag or load is less because the rate of cutting lines of force is reduced, and the meter runs faster. If, however, the meter is found to record too fast for the power passing, the drag magnets are moved toward the circumference of the disc. Here the more rapid rate of cutting lines of force causes a greater reaction and the meter slows down. The meter is calibrated for light load by adjusting the shunt field coil, *S*. A small current is passed through the instrument and its registration compared with a standard instrument. If the meter fails to start or runs too slow, the shunt field coil, *S*, which is adjustable, is moved in toward the armature, *A*. Now the field of *S* is parallel to the field produced by *F-F*, and constantly exerts a pull upon *A*. If the meter runs too fast the coil *S* is moved farther away from *A*, reducing this tendency. If the meter is mounted in a place where there is apt to be vibration, as in a building where machinery is operated, it may tend to creep, due to the pull of the coil *S* on the armature *A*, even though no

load current passes through the field coils, *F*-*F*. To prevent creeping, a small soft iron clip is sometimes placed on the edge of the disc *D*. When this clip gets between the poles of one of the drag magnets, the magnetic attraction tends to hold it there with just sufficient force to prevent creeping. This does not materially interfere with the calibration of the meter.

Changing the full load adjustment affects both the light load and full load adjustment about the same. Changing the light load adjustment 10% alters the full load adjustment only about 1%. Therefore, in calibrating a meter the full load adjustment should be made first.

It is not always convenient to have a large meter run fast enough, nor a small meter run slow enough to correctly register the power. The meter may be adjusted for a suitable speed



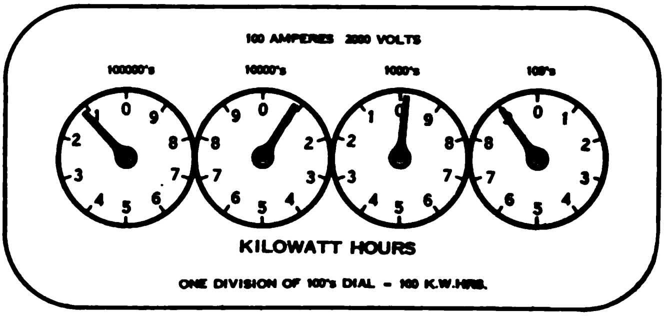
READING - 158 KW HRS

FIG. 236.—158 kilowatt hours.

regardless of the actual power and the registration on the dial corrected by means of a **dial constant.** This is a number by which the dial reading must be multiplied to get the true kilowatt hours. A large meter may require a dial constant of 40 or more; a small meter a dial constant of ½.

The **disc constant** of a watt-hour meter is the fractional part of a kilowatt hour recorded on the dial by one revolution of the disc. It is sometimes marked upon the disc and is employed in the calibration of the instrument. A worm placed on the shaft at *W*, Fig. 235, engages a clock train which rotates the hands on the dials. These dials are connected to each other as in calculating instruments, in which one complete revolution

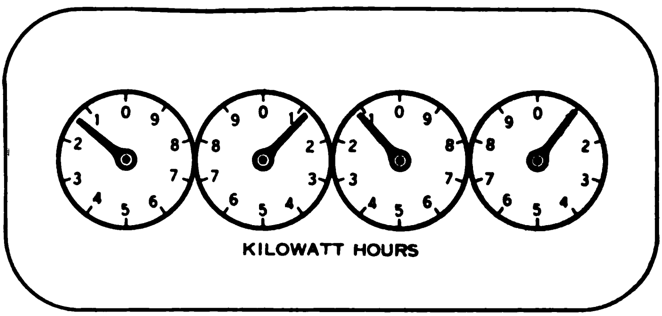
of the hand on the first dial causes the hand on the next dial to move one division. Most meter dials read directly in kilowatt hours. Manufacturers place numbers either over or beneath the dials. These numbers correspond to the number of watt-



READING - 109900 KW HRS.

FIG. 237.—109,900 kilowatt hours.

hours or kilowatt hours registered by one complete revolution of the hand on that dial. Thus, in Fig. 236, the hand on the right-hand dial points to 8. This represents 8 kilowatt hours. The number 10 above this dial would not be indicated until the hand had made a complete revolution. The complete reading



READING - 1111 KW HRS

FIG. 238.—1,111 kilowatt hours.

in this case is 158 kilowatt hours. In other instruments the number above the dial is followed by 's. Thus, in Fig. 237, the number above the right-hand dial is 100's. This is the value of one division on the dial below and not the value of a complete revolution. Thus, as the hand points to 9 on this dial, the

registration for this dial is 900 kilowatt hours, the whole reading being 109,900 kilowatt hours.

As the reading of one dial depends on the reading of the dial to the right of it, the numbers should be set down beginning

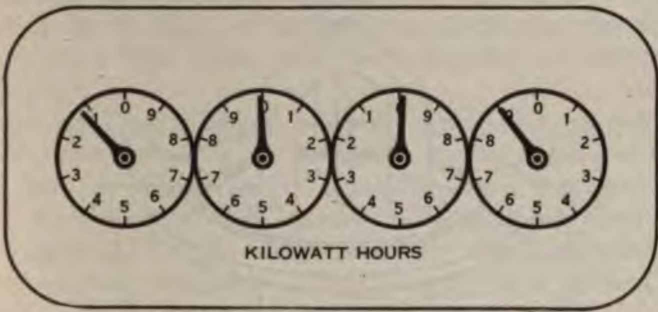


FIG. 239.—999 kilowatt hours.

with the right-hand dial and proceeding to the left. Following this plan, Fig. 238 reads 1,111 kilowatt hours, while Fig. 239 reads 999 kilowatt hours. In this case it will be seen that as

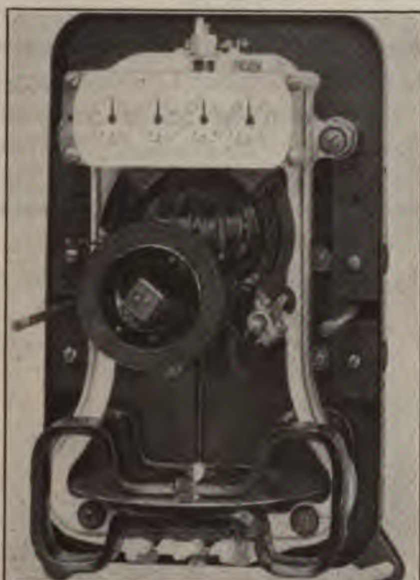


FIG. 240.—Thompson watt-hour meter manufactured by the General Electric Co.

the right-hand dial has not yet reached zero, the one to the left of it cannot be taken as zero, but must be read 9. As this

one is read 9, the one to the left of it must also be read 9, although it appears to be at zero. The one to the left of this must be taken to read zero, although it appears to be at one, but it does not reach one until the one immediately to the right of

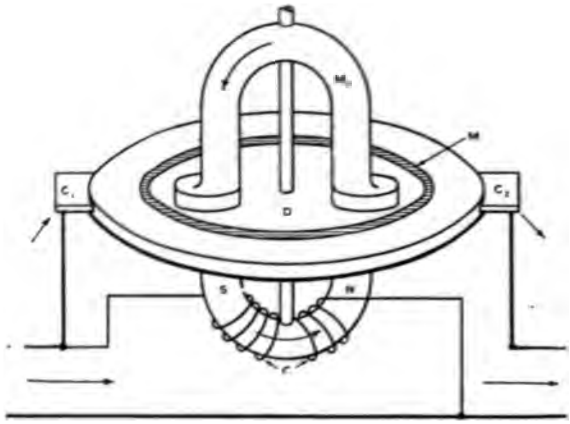


FIG. 241.

it has reached zero. If the right-hand dial now moves to zero, the reading of this meter becomes 1,000 kilowatt hours, instead of 999 kilowatt hours, although all of the dials except the one to the right will have remained in practically the same position.

The older form of watt-hour meter shown in Fig. 235 has been replaced by a much improved design which operates on practi-

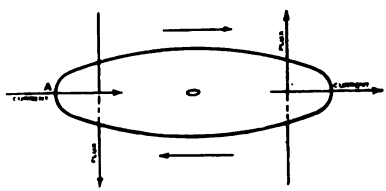


FIG. 242.

cally the same principle, shown in Fig. 240. This instrument differs from the original in that the armature has many more turns of fine wire than the older type and therefore develops a higher torque for a given load. The increased resistance of the armature winding also eliminates all or nearly all of the extra series resistance R, Fig. 235, the remainder being included in the shunt field coil.

While these instruments will work equally well on A. C., because of the absence of all iron in their construction, they are generally used on D. C. only. This is because a superior and much simpler instrument, operating on the principle of the induction motor, has been designed for alternating current measurements. This latter instrument required no commutator or brushes.

Mercury Type of Meter.—Another widely used type of direct current instrument is the Sangamo mercury type of meter, Fig. 241. A copper disc, *D*, is attached to a float and placed in a chamber filled with mercury and mounted upon a vertical steel shaft. The shaft passes through jewel guides and is so carefully balanced in the mercury bath *M* that there is an upward thrust of about 1/10 of an ounce against a jewel which is the only bearing for the moving system. Current enters by a massive lug, *C-1*, and passes through the mercury and on to the edge of the rotating disc. Crossing the disc diametrically, it leaves by the other lug, *C-2*. The direction of the path of the current across the disc is pictured in Fig. 242. Perpendicular to the disc is a magnetic field, produced by a potential coil, *C*, Fig. 241, connected in shunt with the line. This magnetic field completes its circuit through the soft iron yoke *M*-1. The field about the path of the current where it enters the disc at *A*, Fig. 242, is represented in Fig. 243. The perpendicular field due to the potential circuit is shown in this figure, as *N-S*. It will be evident that the flux is concentrated on the right and weakened on the left. The disc, therefore, moves in the direction shown by the arrow. This effect is duplicated where the current leaves the disc. As the strength of the current in the disc is proportional to the load and the intensity of the field due to the potential circuit is proportional to the voltage of the line, the speed of registration will be proportional to the product of the volts and the amperes or the watts. In the top of the instrument is placed another disc which rotates between drag magnets to furnish the load. The instrument is very rugged in construction due to the absence of

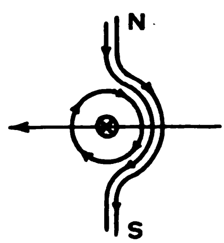


FIG. 243.

all moving wire, commutator and brushes. The complete assembly of a meter of this type is shown in Fig. 244.

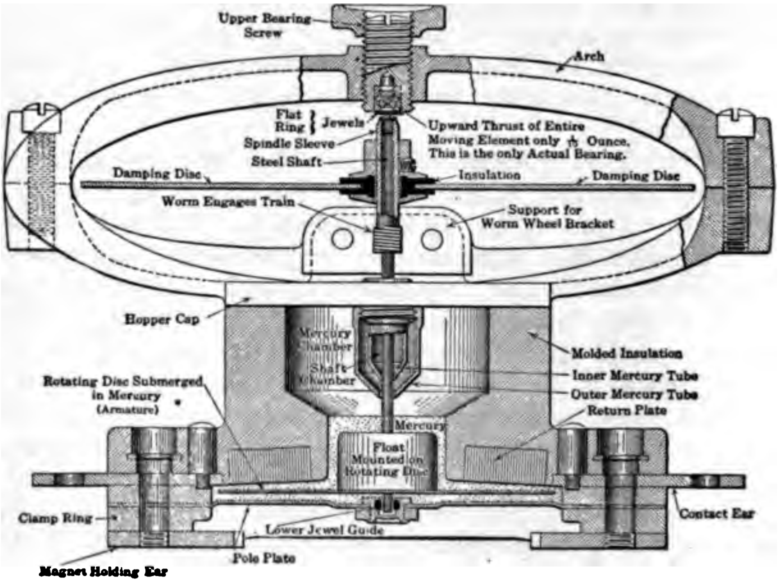


FIG. 244.—Sangamo mercury watt-hour meter.

SECTION VII CHAPTER V

INSTRUMENTS AND MEASUREMENTS

INDICATING WATTMETERS AND WATT-HOUR METERS

1. Explain the principle of operation and construction of an indicating wattmeter. Sketch.
2. Explain the object of the compensating coil in a wattmeter. Sketch.
3. Explain the construction of the Thomson inclined coil wattmeter.
4. Explain the principle and construction of the Thomson watt-hour meter. Sketch. How is it made to record the power and the time? For what kind of circuits is it used?
5. How is a Thomson recording watt-hour meter calibrated for light load and for heavy load? Which adjustment should be made first? Why?
6. What is the "disc constant" in a meter?
7. What is the "dial constant"?
8. Explain the construction of the Sangamo mercury type of meter. What are its advantages? Sketch.

INSTRUMENTS AND MEASUREMENTS

MEASUREMENT OF RESISTANCE

The electrician and engineer have to measure a great variety of resistances. Some of these carry no current except that used to obtain the necessary indications. Others are alive, that is, they are charged to considerable potential or carry considerable current. Depending upon conditions encountered, various measuring instruments are required to properly indicate the value of the resistance in circuits.

Substitution Method

One of the simplest plans of measuring resistance is the **substitution method.** In Fig. 245, let a galvanometer, G, be connected in series with a battery and an unknown resistance, X, by means

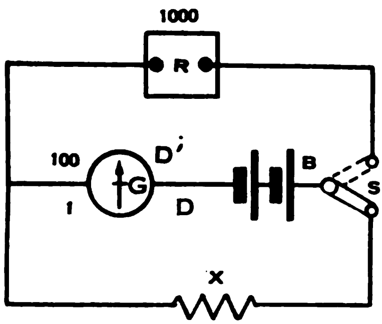


FIG. 245.—Circuits for "substitution" method of measuring resistance.

of a switch, S. Assume a certain deflection, D, to be obtained. Now move the switch into the dotted position which includes a standard adjustable resistance, R. By inserting more or less of these coils, an adjustment may be reached where the galvanometer will deflect the same number of divisions as before. As the deflections are the same in the two instances, the current must be the same. As the currents are the same the resistance in the respective circuits must be the same. Therefore, the unknown resistance, X, is equal to that portion of the resistance box R, now included in the circuit. It will be observed, however, that this method of measurement is limited to an unknown

resistance equal to the maximum resistance which is available in the box, R.

Proportional Deflection Method

The range of measurement may be considerably increased by employing the proportional deflection method. This method is based upon two conditions. First, the galvanometer, G, must be an instrument in which the deflections are strictly proportional to the current. Any permanent magnet type of sensitive millivoltmeter such as the Weston, Model 45, will answer for the purpose. Second, the voltage from the battery, B, impressed upon R and X must be the same. Now assume that with the switch in the lower position, the battery B sends a current through the unknown resistance, X, which gives a deflection of one scale division, D. Then moving the switch to the dotted position, impress the same voltage on the standard resistance box, in which there is plugged into the circuit 1,000 ohms. Assume that a deflection of 100 divisions is obtained in this case, D'. As the deflections are proportional to the currents and the same voltage is impressed upon the two circuits, the resistances are inversely proportional to the currents and therefore to the deflections. Thus:

$$D : D' :: R : X; \text{ from which, } X = \frac{D'R}{D}$$

Applying this formula

$$\frac{100 \times 1000}{1} = 100{,}000 \text{ ohms.}$$

The resistance of the galvanometer should be known and if it is included both in the circuit with R and in the circuit with X, allowance therefor should be made in order to accurately determine the value of X. The foregoing calculation is therefore only approximate. Assume that a galvanometer having a resistance of 100 ohms is used, and that a resistance of 1,000 ohms in R is employed. The deflection D' on R is 100 and the deflection D on X is 1. The formula then becomes:

$$D:D'::(R + 100):(X + 100);$$

$$\frac{D' \times (R + 100)}{D} - 100 = X.$$

$$\frac{100 \times (1000 + 100)}{1} - 100 = 109{,}900 \text{ ohms.}$$

This method is employed in the measurement of very high resistances up to several hundred thousand or a few million ohms.

Fall of Potential Method

The fall of potential method for measuring very low resistances is illustrated in Fig. 246. Here a battery, B, sends a current through two resistances, X, which is unknown, and R which is known. The two are connected in series. A voltmeter similar to the Weston Model 45 permanent magnet type is employed to measure the fall in potential.

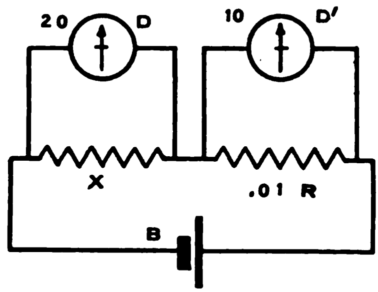


FIG. 246.—Circuits for "fall of potential" method of measuring resistance.

As the currents are the same in the two resistances, the fall in potential will be in direct proportion to the respective resistances. Thus, if the known resistance, R, is 0.01 of an ohm, and the fall in potential across its terminals, D', is 10 divisions on the scale and the fall in potential, D, across X brings about 20 divisions, then

$$D : D' :: X : R; \qquad 20 : 10 :: X : 0.01,$$

$$\frac{20 \times 0.01}{10} = 0.02 \text{ ohms.}$$

Summary.—The last two methods may be best understood by contrasting the facts involved in each case. In the proportional deflection method, the same **voltage** is applied to the two resistances and the deflections are **inversely** proportional to the resistances. In the fall of potential method the same **current** is applied to the two resistances and the deflections are **directly** proportional to the two resistances. In the proportional deflection method the **higher** the resistance the **less** the deflection, hence the **inverse** proportion. In the fall of potential method the **higher** the resistance the **greater** the deflection, hence the

direct proportion. In both cases instruments must be employed in which the deflections are strictly proportional to the currents.

Principle of Wheatstone Bridge

A widely used form of measuring device is the Wheatstone Bridge. This was devised by Christie and applied by Wheatstone. It consists of a divided circuit, Fig. 247, where one branch consists of the wire *A-B*, and the other the wire *R-X*. Assume a current from a battery *B*, of 9 amperes, to enter this divided circuit at the point *e*. It will divide in accordance with the law of branch circuits which is that every branch passes a portion of current inversely proportional to its resistance. If

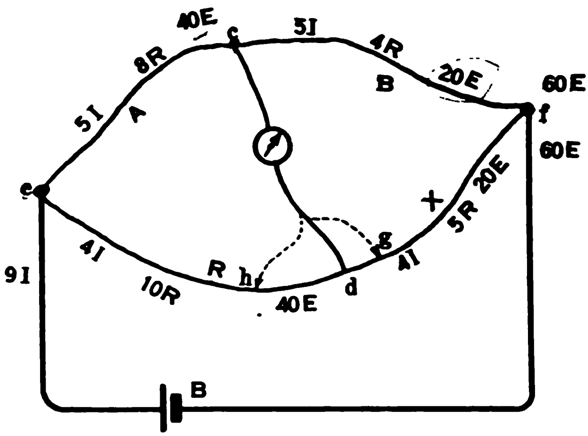


FIG. 247.

the wire *e-c* has a resistance of 8 ohms and the wire *c-f* a resistance of 4 ohms, then the entire resistance of the branch, *e-c-f*, is 12 ohms. If the lower branch has 10 ohms resistance from *e* to *d*, and 5 from *d* to *f*, then the entire resistance of *e-d-f* is 15 ohms. If the resistance of the upper branch is 12 ohms and the lower branch 15 ohms, the ratio of the upper to the lower is 12:15 or 4:5. The current of 9 amperes will divide in these two branches, in the inverse ratio or 5:4 amperes. The 5 amperes going by the upper route through the 8 ohms resistance will fall 40 volts in potential by the time it reaches the point *c*. If this current continued through *B* the potential will fall 20 volts more by the time it reaches *f*. Thus, the total fall of potential through *e-c-f* will be 60 volts. 4 amperes passing through the wire, *R*, which has 10 ohms

resistance, will suffer a drop of potential of 40 volts by the time it reaches *d*. If this current continues through X, which has 5 ohms resistance, the voltage will fall 20 volts more by the time it reaches *f*. Thus, there will be 60 volts drop by the lower branch. This is always true of divided circuits. The fall in potential will be the same through any number of branches in a multiple circuit regardless of their separate resistances. This is true in the case under discussion, where the fact that 5 amperes goes by the upper circuit and 4 amperes by the lower circuit, does not interfere with the total fall of potential reaching 60 volts in each circuit. If the lower end of the wire *c-d* be touched at the point *g* the potential at this point will be lower than at the point *c*. Current will then leave the upper wire and flow across the wire *c-g* to the lower branch. This cross wire is called the **bridge** and explains the name given to this particular form of circuit. If the bridge wire is moved to the point *h*, the potential here will be found to be higher than at the point *c*. Current will then leave the wire *e-d* at the point *h*, and flow up across the bridge wire, entering the upper branch at the point *c*. If the wire *e-d-f* is of uniform resistance, it is evident that by exploring along its length, a point will be found, say at *d*, where the potential will be the same as at *c*. No current will then flow in the wire *c-d*. This condition of balance may be indicated by a galvanometer inserted in *c-d*. If the needle deflects one way a higher potential will be indicated at *c*. If the other, a higher potential at *d*. If the needle fails to deflect at all then the potentials at *c* and *d* are known to be equal. Now when will this condition of balance be obtained? Experiment will show that it is only reached when the ratio of the resistance in the branch R to the resistance in the branch X is the same as the ratio of the resistance in branch A to the resistance in branch B. Now the ratio of R to X is 10 to 5, which is a ratio of 2 to 1. The ratio of A to B is 8 to 4, which is also 2 to 1. There will be an equality of **potentials** at *c* and *d* only when there is an equality of **ratios** between the two branches, as when

$$A : B :: R : X, \text{ from which } \frac{B \times R}{A} = X.$$

Now why should this balance be sought? It is in order that the value of an unknown resistance, X, may be computed when the

resistance of A, B and R are known. Thus, taking the values given in the figure and assuming that X is unknown:

$$\text{If } \begin{array}{l} A = 8 \\ B = 4 \\ R = 10 \end{array} \text{ then } \begin{array}{c} A:B::R:X \\ 8:4::10:X \end{array} \quad \frac{4\times 10}{8} = 5 \text{ ohms for } X.$$

The portions of the circuits A, B, R and X are known as the **arms** of the bridge. A, B and R are usually contained in a resistance box and have adjustable values of suitable range. The X arm is, of course, unknown, and is outside of the bridge box itself. Commercial forms of Wheatstone Bridges usually have a range of measurement from a few thousandths of an ohm to one million ohms or more.

A Wheatstone Bridge never employs as much as 9 amperes or a drop in potential of 60 volts. These large values have simply

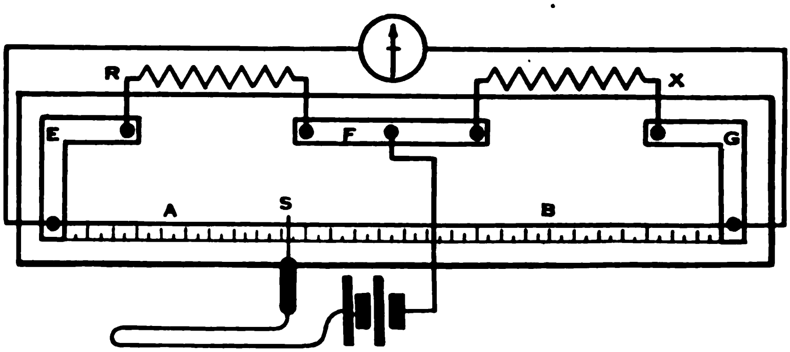


FIG. 248.—Slide-wire form of Wheatstone Bridge.

been employed in the foregoing explanation for convenience. It is customary to employ beween 3 and 10 volts on commercial bridges with very minute currents.

Forms of Wheatstone Bridge

Slide Wire Bridge.—The Wheatstone bridge is made in a variety of forms. One of the earliest of these was the slide wire bridge, shown in Fig. 248. Here a stretched wire of uniform cross-section and resistance, usually of German silver, extends over a scale which is commonly one meter in length. The wire need not be any particular length or resistance. The scale of one meter is used because it is conveniently divided into either 100 centimeters or 1,000 millimeters. The wire should be of relatively

high resistance, preferably about 22 to 26 gauge. The massive copper bars shown at E, F and G serve to establish connections between the different parts of the circuit. The slider, S, is manipulated by hand and is employed to make contact at any desired point on the slide wire. A known resistance is inserted at R and the unknown resistance at X. While this circuit does not appear to closely resemble the diagrammatic form, Fig. 249, nevertheless a comparison between Fig. 249 and Fig. 248 will show that the circuits are identical. Thus, in both cases, current from the battery enters the bridge at the point S, where it divides through A and B. At the extremities of A and B the galvanometer is connected. From these points the current continues from A through R and from B through X, reuniting at the point F, whence it returns to the battery.

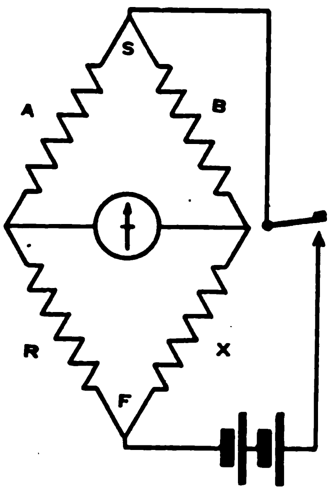


FIG. 249

To manipulate the slide wire bridge, the slider, S, is moved up and down the wire A-B until no deflection is obtained upon the galvanometer. If, when a balance is indicated, the length of the portion A is 40 centimeters and that of B, 60 centimeters, this ratio of the resistance of these two sections is the same as the ratio of R to X. Thus, if R were known to be 100 ohms, then X would be 150 ohms. It will be noticed that while it is customary to know three out of the four resistances involved in a Wheatstone Bridge, in the case of the slide wire bridge, only one, R, need be known provided the ratio of the lengths in which A-B is divided is known. This bridge is suitable for laboratory purposes for obtaining a rough approximation of resistances ranging from 1 to 100 ohms.

Post Office Bridge.—A more practical form of bridge is the Post Office pattern, shown in diagrammatical form in Fig. 250. The actual appearance is that shown in Fig. 251. A series of brass bars of massive cross-section are mounted upon the hard rubber top of a box, which contains a number of resistance coils.

The brass bars are sawed into sections, the adjacent sections being bridged by a coil. These coils are wound non-inductively as shown in Fig. 252, and are normally short-circuited by a plug, 2. There are usually three or more coils between the binding

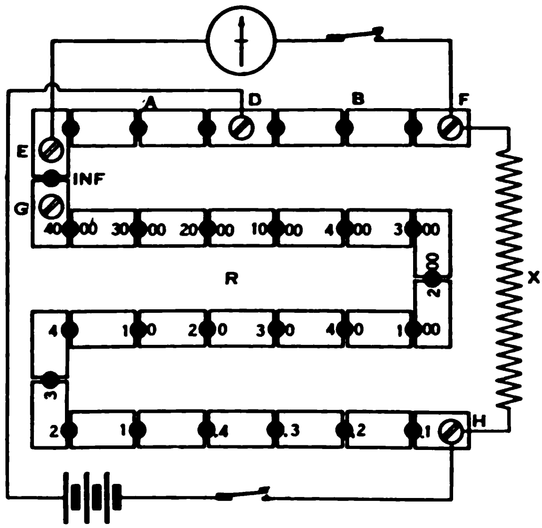


FIG. 250.—Diagram of circuits of Post Office form of Wheatstone Bridge.

FIG. 251.—Post Office type of Wheatstone Bridge, manufactured by the L. E. Knot Apparatus Co.

posts D and E, Fig. 250, and similar coils between D and F. Between E and G is a plug which spans the only open circuit in the bridge. All of the gaps are normally closed by coils. The plug between E and G is called the infinity plug and forms a gap where additional resistance may be inserted to extend the range of the bridge. Between G and H are a series of coils running from 4,000 ohms down to 0.1 of an ohm. This forms an adjustable resistance box of great flexibility. The three coils between A and D constitute the A arm and those between D and F the B arm of the bridge. These are commonly called the ratio arms. The resistance, X, to be measured, is external to the bridge and is connected between F and H. The galvanometer is placed across E-F and the battery between D and H. An examination

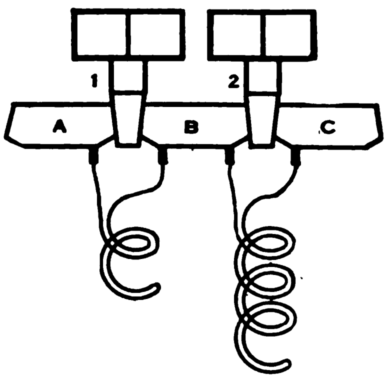


FIG. 252.

of the circuits through this bridge will show them to be identical with the diagrammatical form in Fig. 249. If a ratio of unity is established in A and B, such as 10:10 or 100:100, the amount of resistance which it is necessary to unplug in R to establish a balance against X is identical with X. Thus, if the 100 ohm plug were withdrawn in A, thereby looping in circuit, the coil which it short-circuited, and the 100 ohm plug in B is likewise withdrawn, a ratio of 1:1 is established. If, now, the galvanometer needle fails to show any deflection with 526 ohms unplugged in R, the value of X is 526 ohms, for $A : B :: R : X$, $100 : 100 :: 526 : X$. Hence, $X = 526$.

The combination of coils which are used in the Post Office Bridge insures great flexibility. The smallest resistance which

can be measured with the bridge illustrated, will require 1,000 ohms in A, 10 ohms in B and 0.1 ohm in R. If, under these conditions, a balance is obtained, then to calculate X; $1000:10::0.1:X$. Hence, $X = 0.001$ ohms. The highest resistance that can be measured would be obtained with 10 ohms in A and 1,000 ohms in B. By withdrawing all of the plugs below the infinity gap, a total resistance of 11,111 ohms may be unplugged in R. If, now, a balance is obtained on X, the indicated value of the unknown resistance would be $10:1000::11{,}111:X$. Hence, $X =$ 1,111,100 ohms. The wide range of resistance measurements possible will be seen when it is considered that with the 26 resistance coils which this bridge possesses, there may be obtained

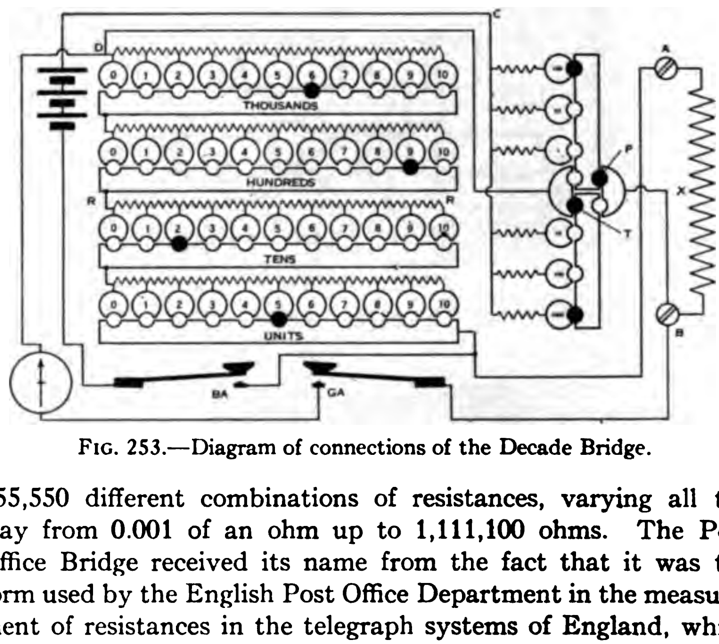


FIG. 253.—Diagram of connections of the Decade Bridge.

555,550 different combinations of resistances, varying all the way from 0.001 of an ohm up to 1,111,100 ohms. The Post Office Bridge received its name from the fact that it was the form used by the English Post Office Department in the measurement of resistances in the telegraph systems of England, which comes under the direction of that department. The chief objection to the above form of bridge is the large number of plugs in series. If these plugs are loose or corroded, it is almost impossible to get a balance or to be sure of accurate results.

The Decade Bridge.—The Decade form of bridge reduces the number of plugs in a series, there being but one in each of the ratio arms and one for each series of coils in the resistance box, nstead of 20. The scheme of connections employed in this

bridge is shown in Fig. 253. By the addition of two additional plugs, *T-P*, connected as shown, it is possible to reverse the position of the ratio arms. This avoids the necessity of considerable duplication of coils in these arms. In the resistance box a single plug is provided in the thousands series and one each in the hundreds, tens and units. By moving this plug horizontally, any value in that series may be inserted in the circuit. Another

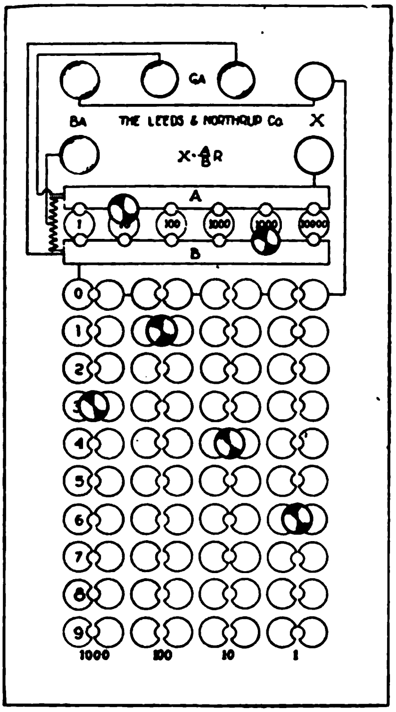


Fig. 254

form of this bridge is shown in Fig. 254. The outside appearance of such a bridge is shown in Fig. 255.

Dial Bridge.—Another form of bridge is the Dial Bridge. The wiring diagram showing internal connections for a bridge of this type built by the Leeds and Northrup Co. is shown in Fig. 256. Here very rugged switches of the commutating type replace the plugs entirely. One sliding switch contact is placed in the thousands series, one in the hundreds, one in the tens and one in the units. There is but one sliding contact for both ratio arms. The outside appearance of this bridge is shown

in Fig. 257. The range is from 0.001 ohm to 9,999,000 ohms and the accuracy is within 0.1 of 1%.

Sometimes in Wheatstone Bridge measurements it is not possible to obtain an exact balance. With one value of resistance in the R arm the needle deflects one way and with the next higher value it deflects the other way. Under these conditions the true resistance may be obtained by interpolation. Thus, for example, with 24.5 ohms in R, assume that the gal-

Fig. 255.—Decade type of Wheatstone Bridge manufactured by the Leeds and Northrup Company.

vanometer needle deflects 9 divisions to the left, while with 24.6 ohms in R the needle deflects one division to the right. The rule under these conditions for finding the true resistance is as follows: Divide the number of divisions obtained with the lowest resistance in series by the sum of the deflections both ways and multiply the quotient by the difference between the lowest resistance and the highest resistance, thus,

$$\frac{9}{9+1} = \frac{9}{10} = 0.9$$

$$0.9 \times 0.1 = 0.09$$

Add to this value the lowest resistance: 0.09 + 24.5 = 24.59. The result is the true value of X. Thus, in the above example:

$$\left(\frac{9}{9+1} \times 0.1\right) + 24 = 24.59 \text{ ohms.}$$

Interpolation is highly accurate when the deflections are nearly equal on each side of zero. This is because the scale divisions

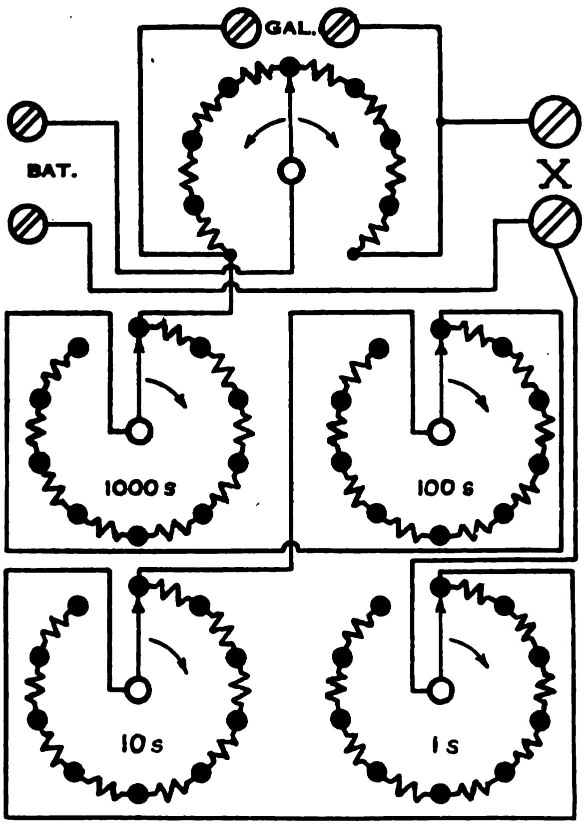


FIG. 256.—Diagram of circuits of Dial Bridge manufactured by The Leeds and Northrup Company.

are uniform across the scale while the magnetic field varies widely for different coil positions. That is, the scale divisions are not proportional to the current in the coil.

The most sensitive arrangement of the arms of a Wheatstone Bridge, that is, the arrangement which will give a maximum deflection of the galvanometer for a given change in the resist-

ance in the R arm, is when A, B, R and X are equal. The best value for the resistance of the galvanometer is the parallel resistance of the arms of the bridge across which the galvanometer is connected, that is, the resistance of the galvanometer should be:

$$G = \frac{(A + B)\ (R + X)}{A + B + R + X}.$$

It is not often that these conditions can be obtained in practice but they represent an ideal which should be approached as closely as possible.

Measurement of Resistance of Cells

The measurement of a live resistance such as a cell of battery on a Wheatstone Bridge involves difficulties because such a cell

FIG. 257.—Dial Bridge manufactured by The Leeds and Northrup Company.

would either aid or oppose the battery used for operating the galvanometer. Fair results can be obtained by inserting two identical cells in the X arm with their e.m.fs. in opposition. After obtaining a balance the two cells should be reversed and a new balance obtained. The average of the two resistances may be taken as the true resistance of the two cells. This divided by two would give the resistance of one cell.

A better method is to employ alternating current for the operation of the bridge, derived from a small induction coil, Fig. 258. Here a few cells of battery energize the coil C. When the key, K, is depressed, the vibrator, V, interrupts the circuit in the primary, P. This induces alternating currents in the secondary, S, which lead to the bridge. Such currents would not affect a galvanometer, hence a telephone receiver replaces this instrument. This is a very sensitive detector of alternating currents. The absence of any sound is an indication of no difference of potential between the extremities E and F. Two cells of battery are connected in opposition at X. The alternating current affects both cells alike. When a balance is obtained, one-

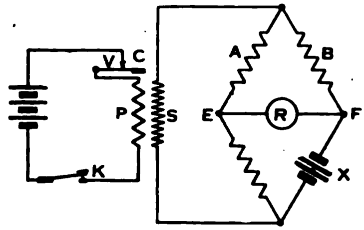


FIG. 258 —Measurement of resistance of two cells of battery by Wheatstone Bridge supplied with alternating zurrent.

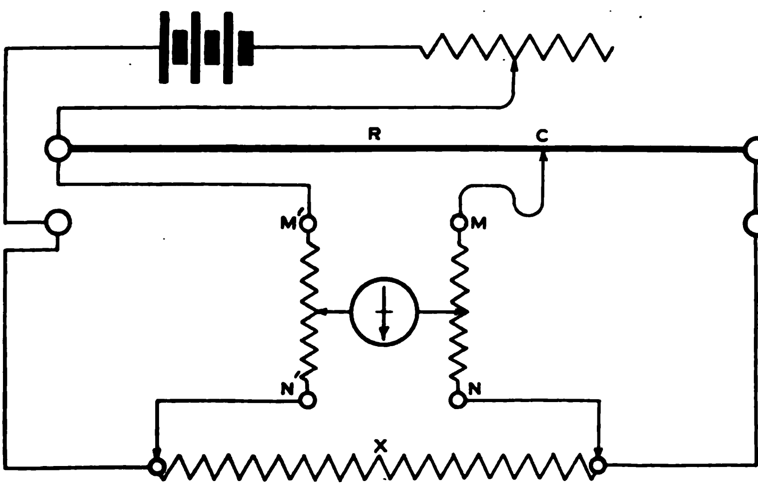


FIG. 259.—Diagrammatical circuit of Kelvin Double Bridge.

half of the indicated resistance in X may be taken as the resistance of one cell.

Kelvin Double Bridge.—The Kelvin double bridge is used for measuring resistances of less than one ohm. A sketch of the electrical circuits is shown in Fig. 259. The ratio coils $M'N'$

and MN must always be so adjusted that the resistances bear the following relation:

$$\frac{M}{N} = \frac{M'}{N'}$$

In actual operation, after having selected a suitable ratio, the contact C is adjusted along the resistance R until the galvanometer is balanced. The value of the resistance being measured is then obtained from the following formula:

$$\frac{R}{X} = \frac{M'}{N'} = \frac{M}{N}$$

The current carried by this bridge is usually from 5 to 15 amperes and the resistance R is usually a combined plug and slide resistance to permit very accurate adjustments. The advantage of this bridge over the types described is that the contact resistance of the connections leading to X is not included in the final results.

SECTION VII CHAPTER VI

INSTRUMENTS AND MEASUREMENTS

MEASUREMENT OF RESISTANCE

1. Explain the "substitution method" of measuring resistance. Sketch.
2. Explain the "proportional deflection" method of measuring resistance. For what kind of resistance is it adapted?
3. If the resistance unplugged in a standard box is 5,000 ohms and a deflection of 50 divisions is obtained upon the galvanometer in circuit therewith, what is the value of the unknown resistance in circuit with the same galvanometer to cause a deflection of 2 divisions? (Neglect the resistance of the galvanometer).
4. If the galvanometer resistance in the preceding example was 2,000 ohms, what would be the actual value of the unknown resistance?
5. If a galvanometer having a resistance of 180 ohms is shunted by a 1/9th shunt and deflects 20 divisions when in circuit with a standard resistance box of 1,000 ohms, what will be the value of an unknown resistance in circuit therewith which brings about a deflection of 2 divisions upon the galvanometer without a shunt?
6. Explain fully the "fall of potential method" of measuring resistance. For what kind of resistance is it adapted?
7. If a galvanometer deflects 15 divisions across a standard resistance of 0.025 ohms in the "fall of potential" method, what is the value of an unknown resistance in series therewith across which the galvanometer deflects 45 divisions?

8. Explain the principle of the Wheatstone bridge. Give diagrammatical sketch and formula.

9. Explain the construction of the "slide-wire" bridge. How many resistances is it necessary to know? What kind of resistance is it adapted to measure?

10. Explain the construction of the "post office" bridge. What are the usual resistances in the ratio arms? What are the usual resistances in the resistance box? What is the smallest resistance that can be measured? What is the highest resistance that can be measured?

11. Explain the "decade" form of Wheatstone bridge. Wherein does it differ from the "post office" bridge. What are its advantages?

12. Explain the "dial" form of Wheatstone bridge. What are its advantages?

13. Assuming a ratio of unity in the ratio arms; if with 26 ohms in the resistance box, the galvanometer needle deflects 4 divisions to the left while with 26.2 ohms in the resistance box the needle deflects 2 divisions to the right, what is the actual value of the unknown resistance?

14. In order that the most sensitive arrangement of the arms of the Wheatstone bridge should be obtained, what should be the resistance of the galvanometer used in any given case?

15. Explain the "opposition" method of measuring the resistance of a battery of 2 cells on the Wheatstone bridge. Sketch.

16. Explain the a. c. method of measuring the resistance of a battery on the Wheatstone bridge. What kind of a receiver is used? Why? Sketch.

17. Explain the Kelvin double bridge. For what kind of resistance measurements is it adapted?

SECTION VIII CHAPTER I

DIRECT-CURRENT GENERATORS

ELECTRO-MAGNETIC INDUCTION

Electro-magnetic induction was discovered by Michael Faraday in 1831. It consists in the induction of an electro-motive-force in a conductor whenever said conductor is moved across a magnetic field. The conductor may be a wire, a coil, or a solid block of metal. The magnetic field may be due to a coil of wire carrying a current, an electro-magnet or a permanent magnet. When either the magnetic field, or the conductor, moves with respect to the other, electro-magnetic induction ensues. This induction consists in the generation of an electro-motive-force within the conductor. It is due to the cutting of magnetic lines of force by the conductor. It is not sufficient for the conductor to move parallel with the magnetic lines. It is necessary that the motion shall be at an angle thereto. The maximum induction occurs when the direction of motion is perpendicular to the magnetic line.

A comparison should now be made between three kinds of induction: **electro-static induction, magnetic induction** and **electro-magnetic induction.** If a charged body is brought in the vicinity of an uncharged body, electro-static induction ensues. A charge opposite in sign to the charge on the inducing body will be induced on the nearest point. The two bodies must be separated by a dielectric. If they touch each other conduction takes place.

If a permanent magnet is brought in the vicinity of a piece of soft iron, magnetic induction ensues. The north pole of the magnet induces a south pole in the end of the soft iron bar nearest it. It is of no importance whether the magnet touches the iron or not. The action is always inductive, not conductive.

When a conductor is approached to a magnetic field in such a way as to cause a cutting of the magnetic lines of force, electro-magnetic induction takes place. This causes the generation of an electro-motive-force in the conductor. The magnet and the conductor may or may not touch. The induction is not due to magnetism or to the conductor, but to the motion.

Electro-static induction consists in the induction of electrical charges. Magnetic induction consists in the induction of magnetic polarity. Electro-magnetic induction consists in the induction of electro-motive-forces, which, if a circuit be provided, will produce electric currents. Suppose the north pole of a magnet, N-S, Fig. 260, is introduced into the end of a coil, C, which is connected to a sensitive millivoltmeter, V. The lines of force from the magnet cut across the convolutions of the coil and an e.m.f. is induced as the magnet is forced downward into the coil. The circuit being closed, this e.m.f. produces a current which causes a deflection of the galvanometer. The current continues as long as the motion continues, but as soon as the magnet is completely within the coil or if at any position it is stopped, then all electro-motive-force and current ceases because the motion has ceased. If, now, the magnet is withdrawn from the coil, the lines of force cut the coil in the opposite direction. The result is a reversal of e.m.f. and the galvanometer needle deflects in the opposite direction. If the magnet is moved quickly into the coil the lines of force are cut more rapidly and a greater voltage is induced and the needle deflects further. The magnitude of the **electro-motive-force depends upon the rate of cutting lines of force.** One line of force cut by one conductor in one second will generate one absolute unit of electro-motive-force, but as one volt is equal to 10^8 absolute units, it is necessary to cut one hundred million lines of force every second in order to generate one practical unit of electro-motive-force, that is, one volt.

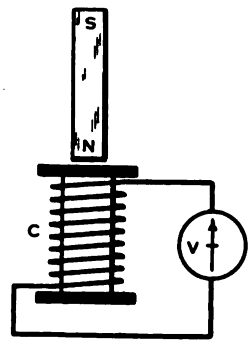


FIG. 260.

It is found that when the pole N is thrust into the coil, the resulting current will flow in such a direction as to produce a north pole at the top of the coil, which opposes the introduction of the magnet into the coil. It is the energy which is required to overcome this opposition which accounts for the generation of the current within the coil. If the magnet is suddenly withdrawn upward from the coil there will be induced a south pole at the top of the coil which, by its attraction, opposes the magnet's leaving the coil. Here again this reaction represents the

energy required to produce the current within the coil. Instead of a magnet and coil, let two coils, A and B, be placed with their axes in line with each other, as in Fig. 261. Let the coil, A, be connected with a battery, controlled by a key, K. The coil B is connected as before with a millivoltmeter. When the circuit is closed on A, the magnetic loops about this coil will project through B in the same manner as when the permanent magnet was introduced into the coil C, in Fig. 260. A momentary deflection of the galvanometer needle is produced, while the current and flux are rising in A. When the current reaches its maximum value, however, the induced e.m.f. in B ceases, because there is no longer any motion between the flux from A and the conductors of B. If, now, the key K is opened, the magnetic loops about A contract, collapsing upon the coil. In so doing they cut in the reverse direction across B in a manner similar to that brought about by the withdrawing of the magnet from the coil C in Fig. 260. The galvanometer needle now deflects in the reverse direction, and continues to deflect while the current and flux in A are dying. A similar result would be produced upon B if the circuit through A and the battery was completed, and the coil A bodily moved toward B. The effect now would be the same as the closing of the circuit while the coil remained stationary, or if while the circuit was closed, A was suddenly withdrawn from B, the effect would be the same as though the circuit through A had been opened. If the circuit through A was closed or the coil A moved toward B, the direction of the current induced in B would be such as to produce a north pole on the side of B nearest to A, that is, the magnetic polarity resulting would resist the motion or with the polarity of A as shown, if the circuit on A were broken or A were moved away from B, the polarity induced in B would be reversed. A south pole on B would then attract the north pole on A and resist the separation of these coils.

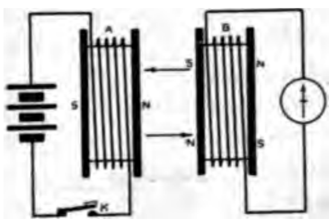


FIG. 261.

It will be remembered that in the case of electro-magnetic dampers in D'Arsonval instruments, the induced currents in the coil or damper always tended to resist the oscillations. It was

the **motion which induced the currents** and the resulting currents opposed the motions.

Lenz's Law

After a careful study of these phenomena, Lenz, in 1834, summed up the effects in what is known as Lenz's Law. He stated that **in every case of electromagnetic induction, the induced currents in their reaction oppose the motion which produces them.** Thus, in Fig. 260, the downward movement of the magnet results in a polarity which opposes this motion. If the motion of the magnet is reversed, the resulting current equally opposes its upward motion. In Fig. 261 the starting of a current in *A* generates an e.m.f. in *B* in the opposite direction. The stopping of the current in *A* generates a current in *B* in the same direction as in *A*. Instead of having two coils with their windings parallel as in Fig. 261, there may be simply two wires as in Fig. 262. Closing the key and introducing current from the battery into *A* causes a magnetic flux which is projected across the parallel conductor *B*, and induces a voltage therein. Opening the circuit at *A* causes a collapse of the flux across *B* and induces a reverse voltage. It is in this way that cross talk occurs between parallel telephone lines.

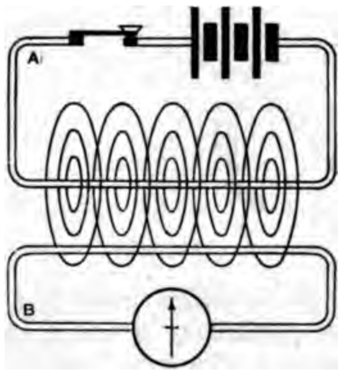


FIG. 262.

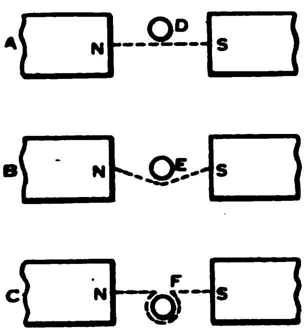


FIG. 263.

In the case of a generator the following explanation has been used by the author to enable the student to have something more concrete to work with than has ordinarily been given in other texts. A conductor, *D*, Fig. 263, is caused to move across a line of force in a magnetic field as at *A*. As the conductor is moved downward into the position *E*, the lines of force bend. Now finally,

when the conductor reaches the position, *F*, the line of force is kinked around the conductor in a loop of force, which finally breaks and snaps together again above the conductor. It will be remembered that when a current from a battery was passed through a conductor there resulted a magnetic field about the conductor. If, now, by mechanical means, it is possible to whip or kink a magnetic line of force about or around the conductor, the result will be an e.m.f. in the conductor. The whole object sought in a dynamo is to cause magnetic whirls about the conductors by rapidly projecting the conductors across a magnetic field, the result being an electro-motive-force in the conductors.

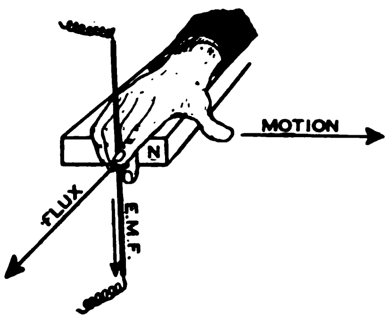


FIG. 264.

Fleming's Rule

The relative direction of the electro-motive-force resulting from cutting lines of force may be ascertained by a study of Fleming's rule, pictured in Fig. 264. Here, suppose the north pole of a magnet is grasped by the right hand so that the flux is projected in the direction of the forefinger, extended as shown. If now a conductor is moved across this line of force in the direction indicated, which may be represented by the thumb extended, the direction of the induced e.m.f. is downward, which may be represented by the second finger. Thus, if the thumb, forefinger and second finger of the right hand be extended, each in a direction at right angles to the other two, the forefinger represents the direction of the flux, the thumb represents the direction of motion and the second finger the direction of the induced e.m.f. It must be borne in mind that the thumb represents the direction of motion of the conductor and not that of the flux motion.

When induction takes place from one circuit, *A*, Fig. 262, to an adjoining circuit, *B*, electrically insulated therefrom, it is called **mutual induction.** This term applies to the coils *A* and *B* in Fig. 261 and to the action between the primary and the secondary of induction coils. If a current from a battery is

led through a thousand feet of number 20 wire, stretched in space as a straight line, the current will rise practically instantaneously to the value determined by its resistance and the voltage applied. If, now, this wire is wound in a coil as in Fig. 265, and an e.m.f. of 10 volts is applied to its terminals, the ultimate strength of the current would be one ampere if the resistance were 10 ohms. But the current would not rise instantaneously to this value, for the following reason: The instant the current started to flow through the convolutions A, the magnetic field about A would be projected across B and induce an e.m.f. therein in the opposite direction to that in which the current was flowing. This would oppose the flow of current in A. In a similar way the magnetic flux about all the conductors

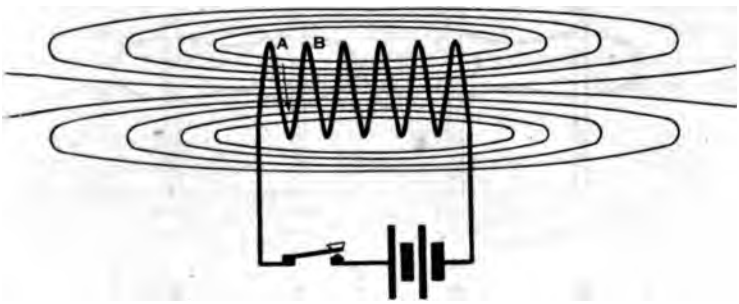


FIG. 265.

is projected across all of the conductors in the coil and generates in each one an opposing e.m.f. The current, therefore, has to slowly climb toward the maximum value determined by the resistance against this opposing electro-motive-force. If the circuit is broken and the current begins to die out, the magnetic loops collapse across the adjacent conductors in the opposite direction. This produces an e.m.f. which tends to keep the current going. Thus the circuit opposes any change in the current value therein. This is inherent to a coiled resistance. It is called self-induction. Self-induction may, therefore, be defined as an inherent property of a coiled conductor by virtue of which it is opposed to any change in current value therein. This is another illustration of Lenz's Law.

Consider two wires, A and B, Fig. 266. Assume a current to be flowing as indicated in A, with the resulting magnetic field

about it in the direction shown. Assume a parallel conductor, *B*, which is moved toward *A*. *B* will indent the magnetic loop about *A* as shown, causing the flux to circulate around *B* in the opposite direction. This will be equivalent to a current flowing in *B* in the opposite direction to the current in *A*. The same effect would be produced if a current were suddenly started in *A*; a current would be induced in the opposite direction in *B*. This is emphasized by an end view of these conductors at the bottom of the figure.

Next consider the conductor, *A*, carrying a current downward

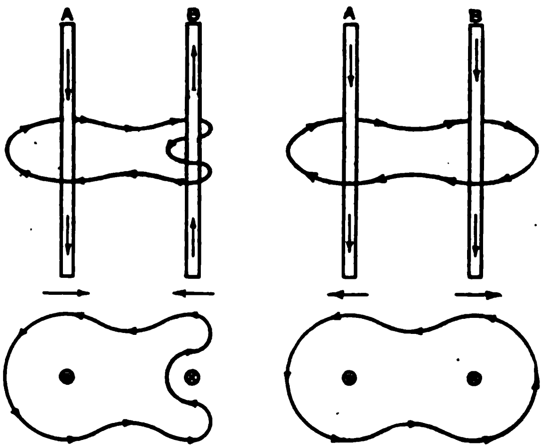


FIG. 266. FIG. 267.

with the magnetic flux about it in the same direction as before. Parallel therewith is another conductor, *B*, which is now assumed to be moved away from *A*. The magnetic flux is now bent outward and the tendency is for this flux to circulate around *B* in the same direction as around *A*, Fig. 267. This is equivalent to a current in the same direction in *B* as in *A*. An end view of these conductors at the bottom of the figure shows the arrangement of the flux in this case. The same effect would be produced in *B* if the current suddenly ceased in *A* instead of moving the conductors apart. The resulting magnetic fields and the corresponding direction of induced currents in these two cases should be given careful study.

SECTION VIII CHAPTER I

DIRECT-CURRENT GENERATORS

ELECTRO-MAGNETIC INDUCTION

1. Explain how electro-magnetic induction takes place.
2. What various things govern the magnitude of the induced e.m.f.?
3. Sketch a coil connected to a galvanometer. If the south pole of a permanent magnet is thrust into this coil, mark the resulting polarity of the coil. If the magnet is withdrawn, mark the resulting polarity.
4. If a permanent magnet is inserted within a coil connected to a galvanometer, when will the induced e.m.f. be a maximum? When will it be a minimum?
5. Sketch two parallel coils. Connect a battery and key in circuit with one and a galvanometer in circuit with the other. Under what conditions will the induced e.m.f. be a maximum? When will it be a minimum? Assuming a given polarity for the first coil, mark the resultant polarity of the second coil. (*a*) When the circuit on the first coil is closed. (*b*) When the circuit is opened.
6. State Lenz's Law.
7. State Fleming's Rule.
8. Explain mutual induction.
9. Sketch two parallel wires: *A* carrying current in given direction, *B* connected to a galvanometer.

   (*a*) Mark the direction of the current in *B* and the resulting direction of the magnetic lines of force around both wires if *A* and *B* are approached to each other.

   (*b*) Mark the direction of the current in *B* and the resulting direction of the magnetic lines of force around both wires if they are moved apart.

DIRECT-CURRENT GENERATORS

COMMUTATION

A generator is a machine for converting mechanical energy into electrical energy. It is not a source of power. It contains no energy. It will give out power from its brushes only in proportion to power put in at its pulley. Mechanical power is usually applied to a generator from a steam engine, a gas engine or a water wheel. The machine is designed to transform this power into electrical energy. The percentage of power which it will convert depends upon its size. Very small machines will convert 60 or 70% of the energy which they receive. Very

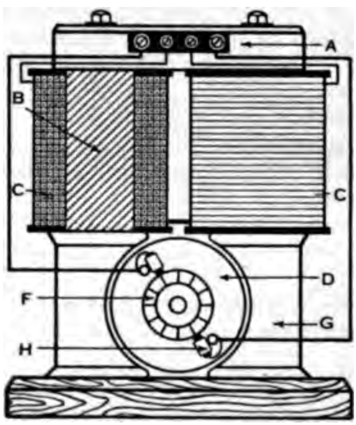


FIG. 268.

large machines absorbing from 1,000 to 10,000 horse power will deliver, in the form of electrical energy for useful purposes, 98 or 99% of the power which they absorb.

There is no electrical significance in the word "dynamo." The word literally means power. A dynamo machine is a power machine. A dynamo-electric machine is an electric power machine. It is customary to refer to large machines of this kind as electrical generators.

It may be said that the essential parts of a steam engine are

a piston and a cylinder. All the other refinements are for the purpose of keeping the engine going. In a similar sense it may be said that the essential parts of a generator are a magnetic field and a system of conductors. The refinements consist in a means for producing relative motion between the two, for

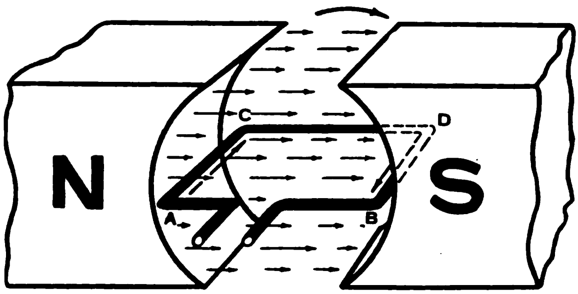


FIG. 269.

collecting the current and for maintaining the field. Fig. 268 represents an early form of generator devised by Edison. It consists of a field structure consisting of the yoke or keeper, *A*, the field core, *B*, the magnetizing coils, *C*, the field poles, *G*, the armature, *D*, the commutator, *F*, the collecting brushes, *H*, which

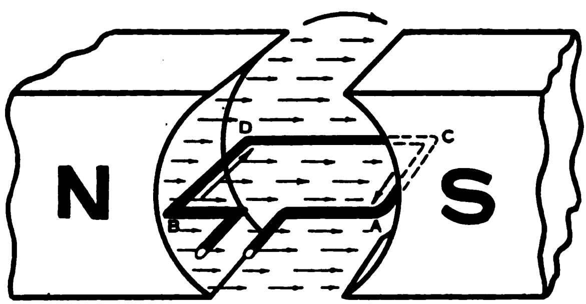


FIG. 270.

are mounted in brush holders and attached to a rocker arm, as shown, for the purpose of altering their position.

Electro-motive-forces are produced in a generator by moving a system of conductors, as illustrated by the simple rectangle *A-B-C-D* in Fig. 269 across a magnetic field, *N-S*. If the conductor *A-C* moves up across the field cutting magnetic lines of force, an e.m.f. will result which urges a current backward from

A to *C*. At the same time the conductor *B-D* is moved down across this field, generating an e.m.f. in the direction *D-B*. These two e.m.fs. will be added together in series across the back of the rectangle where the current will flow from *C* to *D*.

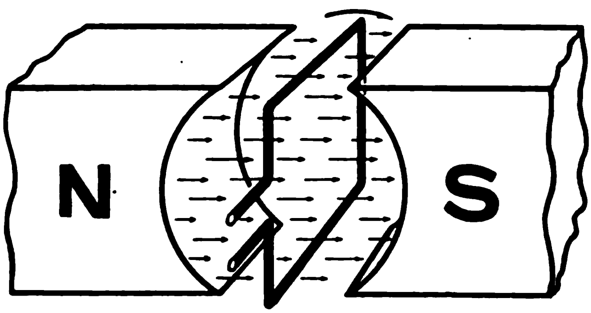


FIG. 271.

If the rectangle be moved through a half revolution the conductors will assume the position shown in Fig. 270. Here *B-D*, which was moving down through the field, now moves up, while *A-C*, which was moving up, now moves down. The e.m.f. will evidently reverse in these two conductors. Midway between these two positions the conductors would stand in the plane shown in Fig. 271. Here they are moving parallel to the lines of force without cutting them, hence there will be no voltage induced. If a pair of collector rings, *H-L*, Fig. 272, are connected one to each end of this rectangle of wire, the current which alternated within the rectangle with each half revolution would be conveyed by the brushes to an external circuit where it would also alternate. Practically all generators produce alternating electro-motive-forces in their windings. This is inevitable in view of the principle which is involved. A current cannot flow unless a circuit exists. Consider such a circuit at *A*, Fig. 273. Linked with this circuit is a magnetic loop of force, *B*. In order to generate an e.m.f. in

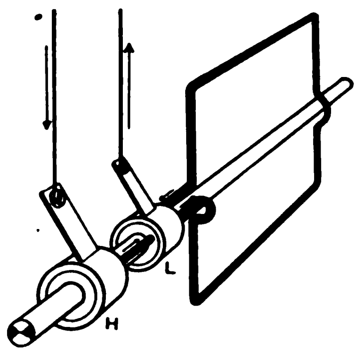


FIG. 272.

A it is necessary to cut the magnetic loop *B* with the conductor *A*. Having cut the magnetic loop to generate an e.m.f. in *A*, it cannot be cut again except in the reverse direction, and with each reversal of direction of cutting the direction of the induced e.m.f. reverses. It is, therefore, impractical to cut a magnetic field which consists of closed loops of magnetic force in one direction without eventually cutting it in the reverse direction, which therefore involves a reversal of the e.m.f. generated and the resulting current which flows. The single exception to this general rule is a special form of generator having one or, at most, twelve conductors, known as a unipolar or acyclic

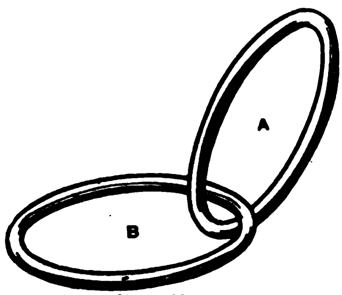


FIG. 273.

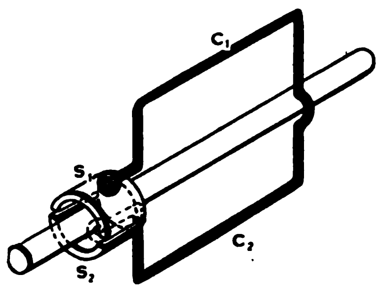


FIG. 274.

machine. Such machines are limited in application and have a low voltage.

In order to supply the external circuit with a uni-directional current it is necessary that the elementary coil already referred to shall be provided with a commutator. The simplest form of this device is shown in Fig. 274. Here a single metallic ring is cut in half and the two ends of the rectangle terminate one on each half. When the current reverses in the two conductors C_1 and C_2, at the end of each half revolution, the connections between the segments, S_1 and S_2, to the brushes also reverse. A reversal of the connections between the segments and the brushes simultaneously with a reversal of the current in the two conductors, C_1 and C_2 prevents a reversal of current in the external circuit leading to the load. The current that would be delivered by the rectangle with slip rings, shown in Fig. 272, is pictured in Fig. 275. Here a line of zero current and potential, *A-B*, corresponds to the conditions when the rectangle is in the posi-

tion shown in Fig. 271. A wave of current in a positive direction is pictured above the line. This would be obtained when the rectangle took the position shown in Fig. 269. A wave of current in the reverse or negative direction corresponds to the position of the rectangle shown in Fig. 270. Fig. 275 gives a graphic

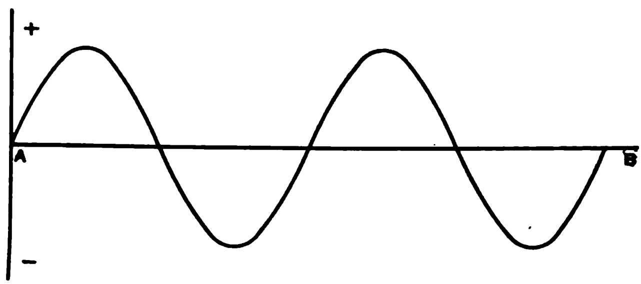


FIG. 275.

representation of the alternating e.m.f. and resulting current produced by a single coil in a simple bi-polar field.

If now the rectangle be provided with a two segment commutator as shown in Fig. 274, the current in the external circuit will not alternate as in Fig. 275, but each reverse impulse within the rectangle is made to flow in the external circuit in the same direction as the original impulse due to the action of the commutator.

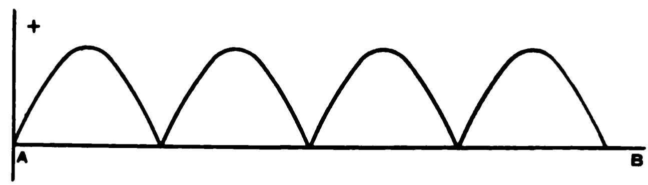


FIG. 276.

This is shown in Fig. 276. This pictures a uni-directional current which, however, is by no means continuous. While the current does not reverse, it nevertheless pulsates between zero and maximum values all in the same direction. If, instead of the elementary rectangle shown in Fig. 274, the armature contains two sets of coils as in Fig. 277, then when the current in one set of coils is zero, due to their occupying the position shown in Fig. 271, the other set would be in the maximum position as in Fig. 270. If this second impulse is impressed upon the same

external circuit the currents of one set would be a maximum when the others were zero and vice versa. The delivered voltage and current would not pulsate now as in Fig. 276, but would fluctuate slightly as in Fig. 278. Modern direct-current armatures contain a large number of coils in which the successive electro-

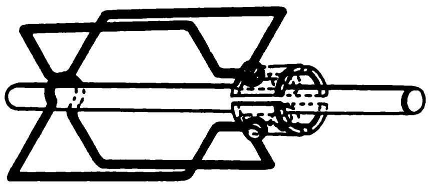


FIG. 277.

motive-forces follow each other so closely that there is practically no pulsation. The waves of current and e.m.f. now obtained are represented by the curve in Fig. 279.

One of the most vital parts of a direct-current dynamo is the

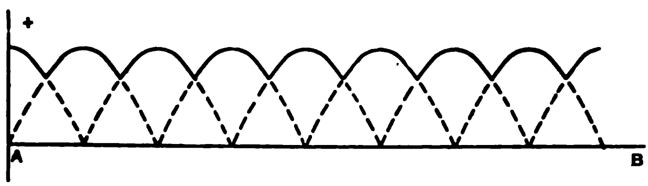


FIG. 278.

commutator. Early commutators were made with segments of brass and insulation of fiber. These proved entirely inadequate. Modern commutators are all made of pure copper with insulating segments of mica. No insulating material other than mica has

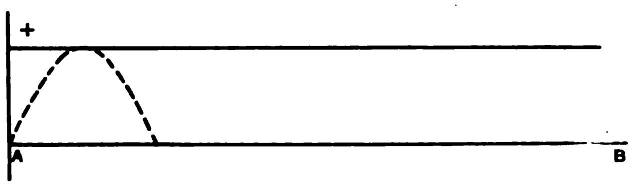


FIG. 279.

been found satisfactory, with the single exception that small commutators have in recent years been successfully made with a molded Bakelite preparation.

Mica has the advantage of not deteriorating under pressure,

of being fireproof and not absorbing moisture. The shape usually given commutator segments is shown at C in Fig. 280. An end view shows the taper of the segments at M, Fig. 281. The segments are usually dovetailed at their ends, having a massive mica insulation at G and H, as well as on either side. Beveled rings of metal at F forced inward by nuts, shown at E, serve to thoroughly clamp the segments in place. A lug or neck extends

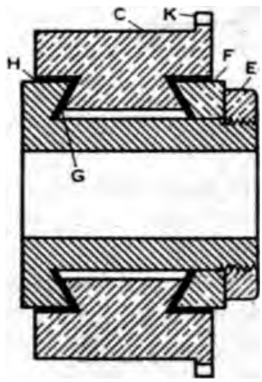


FIG. 280.—Sectional view of commutator showing shape and arrangements of segments and insulating material.

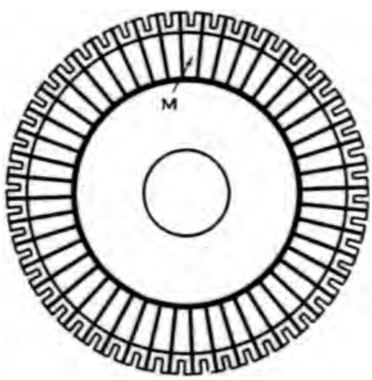


FIG. 281.—Sectional view of end of commutator showing taper of the segments and slots for coil connections.

outward at K from each segment for the purpose of connecting the terminals of the coils.

The magnetic field of generators may be supplied either by permanent magnets or electro-magnets. Permanent magnets are only used in small machines for telephone ringers and for automobile ignition. All large generators have electro-magnets. These may be supplied with current derived from the machine itself in which case the machine is said to be **self exciting,** or they may be energized by means of current derived from an outside source. In the latter case the machine is said to be **separately excited.** Direct-current machines are generally self exciting. Alternating current is not suitable for maintaining the field, hence such machines are generally separately excited.

SECTION VIII CHAPTER II

DIRECT CURRENT GENERATORS

COMMUTATION

1. Define an electrical generator. Name its principal parts.
2. What kind of currents are produced in practically all generators?
3. Explain the process of commutation. Sketch.
4. How are commutators constructed? What materials are suitable for insulation? What features in design will contribute to long life for a commutator?
5. How is the magnetic field provided in most generators? How is the initial magnetism supplied?

DIRECT-CURRENT GENERATORS

TYPES OF ARMATURES

Siemens "H" Armature

The first armature was devised by Dr. Siemens and consists of a single coil, Fig. 282, wound in two rectangular slots. It is called the Siemens "H" armature because of its resemblance to the letter H. The voltage of such an armature would be greater than that in the elementary rectangle in proportion to the number of convolutions employed. The wave of e.m.f. would still be a simple alternating one. Dr. Siemens improved this armature by using a cylindrical drum with a uniformly distributed winding which occupied the entire surface, Fig. 283.

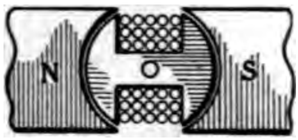


FIG. 282.

Ring Armature

Pacinotti, an Italian, invented a ring type of armature in 1860. He did not exhibit it until 1873. About 1870, Gramme, a Frenchman, reinvented the ring type of armature after which due credit

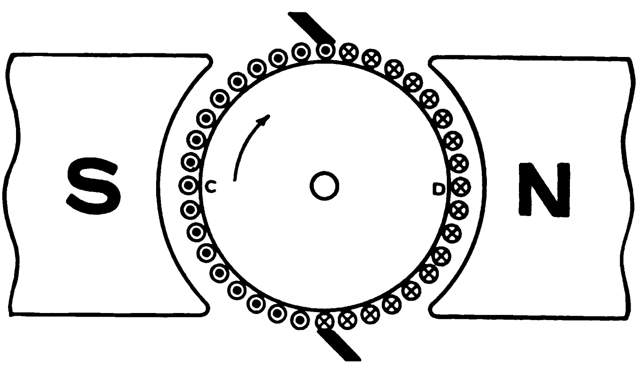


FIG. 283.

was given to Pacinotti. This armature consisted of an iron ring mounted on a nonmagnetic spider with coils that surrounded the core as in Fig. 284. The winding is continuous and when com-

pleted the last end is connected to the first end, thus closing the circuit. When the two ends of the winding are so connected, it is called a closed coil winding. At equidistant points taps are taken to the commutator. Applying Fleming's rule it will be seen that the conductors on the left rising through the magnetic field generate an e.m.f. which urges a current forward. All of the conductors on the left side of the armature are in series and contribute their respective voltages to the total. All of the conductors on the right side of the armature are simultaneously moving downward through the field. These likewise add in series. The two halves of the winding thus constitute two sources of current having equal electro-motive-forces but con-

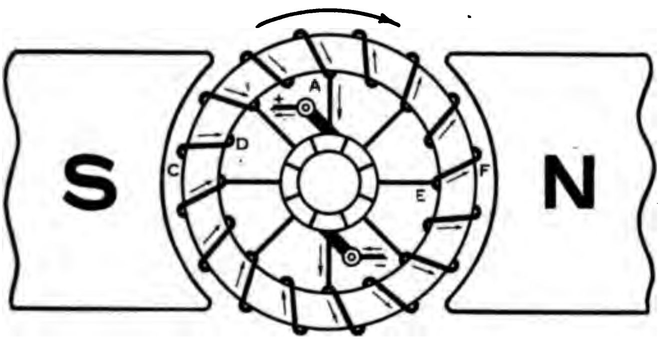


FIG. 284.

nected in multiple. The connections lead the current from the two halves to the point A, where they unite in multiple, passing to the segment and leaving by the positive brush to the external circuit. The two currents, returning by the negative brush, divide into the two halves of the winding from which they emanated. The magnetic flux entering the armature from the north pole does not cross the armature diametrically but follows the iron above and below the shaft. Thus the conductors on the inside of the core do not cut lines of force. It is necessary that this should be the case, otherwise these conductors would generate electro-motive-forces opposite to those on the outside of the armature.

Drum Armature

In the Siemens drum armature the conductors occupy the outside of the core entirely, Fig. 283. Although the windings are

more complex than the simple arrangement used in the ring armature, the results are precisely the same. It makes no difference whether the current in conductor *C*, Fig. 284, returns through conductor *D*, and the current in conductor *E* returns in conductor *F*, or whether the current in conductor *C*, Fig. 283 returns through conductor *D*, the e.m.fs. and magnetic fluxes will be identical in the two cases. Assuming a given flux and speed, the voltage of an armature depends upon the number of conductors in series while the current which may be drawn depends upon the size of wire with which it is wound.

Slotted Armature

The chief feature of Pacinotti's invention was the employment of slots in which the winding was embedded. These slots may be used on either ring or drum machines. For many years the ring type of armature was in favor. It could be more readily insulated and was adapted for high voltages. With improve-

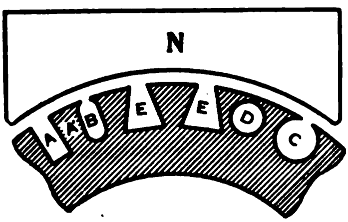


FIG. 285.

FIG. 286.

ment in design, however, it was ascertained after much experimenting that the drum type of armature was in many particulars superior to the ring type. The ring construction is not generally used today. Small machines are invariably built with a drum type core, while large machines use a core resembling the ring in that it is open internally and is carried on a spider but uses a modified drum winding.

Fig. 285 illustrates some of the forms of slots employed in modern armatures. The most widely used slot is the rectangular form shown at *A*. These slots should be preferably from four to six times as deep as they are wide. Shallow slots do not give an economical construction. As the slots are of uniform width throughout their depth, the tooth separating them, *A'*, must taper toward its root. It is evident that the slot could not be made very deep without producing a very narrow tooth root.

This crowds the flux into a very small space, in fact the flux density is greater at the tooth root than in any other part of the magnetic circuit of a generator, often reaching as high as 130,000 lines per square inch. The advantage of this wide open slot construction is that it permits the use of formed coils, that is, coils which are wound upon a form and taped up as a unit before they are inserted in the slot. It also insures somewhat better ventilation, allowing for the radiation of the heat generated in the winding provided the slot is not made too deep.

The second form is the partially closed slot and is shown at *B*. This does not admit of a formed coil for the narrow opening allows the winding of but one conductor at a time. This style is frequently employed in alternating current machines. It does not give quite as good ventilation as the open slot, but the wide surface of the resulting teeth reduces the reluctance in the air

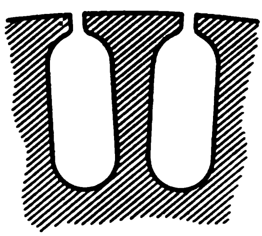


FIG. 287.

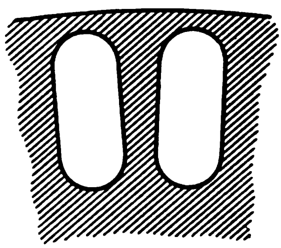


FIG. 288.

gap and gives a quieter running machine. Slot *C* is a modern form of partially closed slot used in fan motors.

Slot *D* is not a slot at all but a hole beneath the surface for a completely embedded winding. It usually carries a single conductor which is driven into place from the end.

An unusual form of slot employed at one time by a large manufacturing firm is shown at *E*. It is triangular with a very narrow opening which admits of a wide tooth with a very narrow root.

The chief advantage of slotted or embedded windings is that the conductors are more rigidly attached to the core and the reluctance of the magnetic circuit is lower than where they are placed wholly on the surface. In the older type of armature having a smooth surface, as in Fig. 283, the air gap consisted not only of the space required for clearance but included in addition

the space occupied by the winding. This involved a high reluctance which required excessive ampere turns on the field structure to produce the proper flux density.

All modern machines have slotted armatures. Of the three varieties employed today, the open slot is commonly used for direct-current machines and the semi-closed slot for alternating-current machines. The entirely closed slot is rarely used. Figs. 286, 287 and 288 represent these three types on an enlarged scale.

SECTION VIII CHAPTER III

DIRECT-CURRENT GENERATORS

TYPES OF ARMATURES

1. Explain the construction of the Siemen's "H" armature. In what kind of machines is it employed? What are its advantages and disadvantages?

2. Explain the construction of the Gramme ring armature. How is it wound? Sketch.

3. Explain the construction of a drum armature. How is it wound? Sketch.

4. Explain the construction and advantages of a slotted armature. Sketch various forms of slot. State their relative advantages.

5. Sketch a ring armature connected to a commutator in a magnetic field. Indicate direction of rotation, direction of induced currents and polarity of brushes.

DIRECT-CURRENT GENERATORS

ARMATURE CONSTRUCTION AND DESIGN

There are **three losses** encountered in every armature:

The I^2R or copper loss in the winding.
The hysteresis loss due to magnetic friction in the core.
The eddy current loss in the core.

The Copper Loss.—The copper loss is the power lost in generating heat in the windings. The power lost in a circuit is proportional to the square of the current and the simple resistance. For an armature of a given capacity the current is obviously fixed. The only factor which can be varied in order to reduce the copper loss to a minimum is therefore the resistance. The length of the

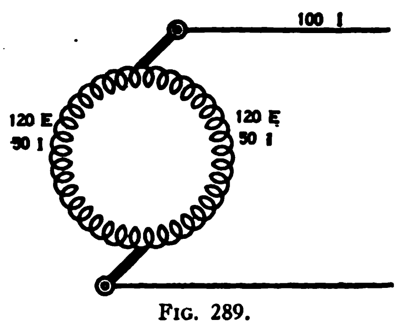


FIG. 289.

armature winding should be short to make this as small as possible. This length cannot be indefinitely shortened, however, without reducing the number of conductors, which would reduce the voltage generated. The cross-section of the copper, however, may be increased, which would reduce the resistance. Experience indicates that an allowance of from 600 to 1,200 circular mils of copper should be made for each ampere which an armature conductor is to carry.

Consider an armature, Fig. 289, delivering 100 amperes. As the current is derived from the two halves of the winding in multiple, each half must contribute 50 amperes. In a machine of

this size suppose an allowance of 800 circular mils per ampere be made:

$$50 \times 800 = 40{,}000 \text{ circular mils required.}$$

This corresponds to a No. 4 wire. Because of the increased difficulties in radiating heat it is necessary to allow more copper per ampere in large machines than in small ones. For example, in fan motors an allowance of 300 circular mils per ampere is often sufficient, while in machines of several thousand kilowatts it is necessary to allow 1,200 circular mils per ampere. In general, high speed machines use a smaller cross-section of conductor per ampere than slow speed machines, due to their better cooling characteristics. This is also true of machines provided with blowers.

The Hysteresis Loss.—When an armature rotates in a magnetic field the magnetic molecules held in a horizontal position by the field poles must necessarily turn a complete somersault in the surrounding mass of iron for each revolution of the armature. If the entire number of molecules accomplish this acrobatic feat there must be considerable friction, and friction means heat. Heat means an expenditure of energy. The denser the magnetic field the greater the loss. Dr. Steinmetz discovered that the hysteresis loss is approximately proportional to the 1.6 power of the flux density, ($B^{1.6}$). The flux density in armatures varies from as low as 50,000 or 60,000 lines per square inch in the core, to as high as 130,000 lines per square inch in the tooth root. To reduce the hysteresis loss it has been found advisable to keep the flux density within the above range and to use the softest and most permeable grades of specially prepared iron or soft steel.

The Eddy Current Loss.—Early experiments with electrical generators resulted in excessive heating of the armature cores. Foucault discovered that this was due to the generation of currents in the core as well as in the windings. Consider the conductor, *E-C*, Fig. 290, to be moving away from the observer across a magnetic field. An e.m.f. would be induced urging a current from *E* to *C*, while a current would flow in series therewith from *D* to *F* through the conductor on the opposite side of the armature. This current in its insulated path could be collected at the terminals for useful purposes. The iron core of the armature

immediately adjacent to these two conductors is moving with them across the same field at the same rate. There will, therefore, be induced in the core an e.m.f. which would be of the same value as that induced between E and C, and this e.m.f. would urge a current from K to H. On the opposite side of the armature an e.m.f. would be induced between I and J of the same

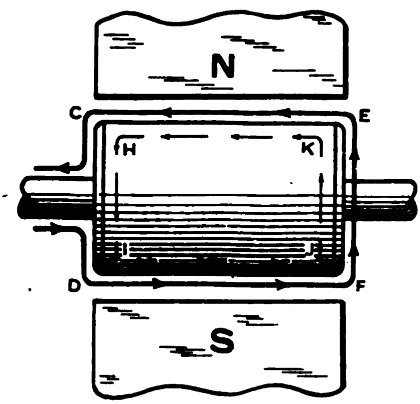


FIG. 290.

value as that between D and F. This electro-motive-force in the core would establish a current which would flow from I to J, across the end, from J to K, thence back from K to H and across the other end from H to I. If the resistance of this path were low, say one-thousandth of an ohm, and the e.m.f. induced were 5 volts, the resulting current would be 5,000 amperes. As the

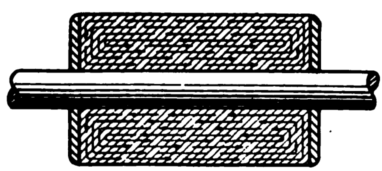


FIG. 291.

heating effect is proportional to the square of the current, the result would be that the core would rise in temperature and the windings would be abnormally heated from within. These currents might circulate across the entire diameter as shown in Fig. 290, or in eddies as indicated in Fig. 291. These are known as **eddy** or **Foucault currents.** The remedy was to sub-

divide the armature parallel to the magnetic flux but at right angles to the induced e.m.fs. If an armature were broken up into sections as shown in Fig. 292 and these sections were insulated from one another, the induced e.m.f. in one section from B to A might be so small that a comparatively feeble current would be urged across the diameter from A to C, while the e.m.f. from C to D would find difficulty in forcing this current back from D to B. While the e.m.fs. are broken up into small values

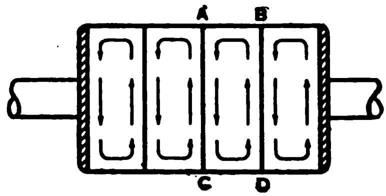


Fig. 292.

and the currents reduced in magnitude, they nevertheless represent a considerable waste of energy. If, however, the armature is finely subdivided into laminations approximately $\frac{1}{64}$ of an inch thick, as in Fig. 293, the induced electro-motive-forces from one face of a lamination to the opposite are so minute that they are practically incapable of establishing a current across the diameter of the disc. All modern armatures are thus laminated and when the laminations are sufficiently thin, eddy currents are

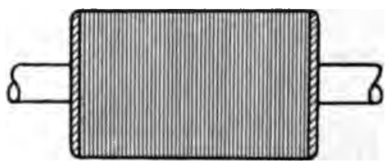


Fig. 293.

practically eliminated. The discs are slightly insulated from each other by a coat of japan. They need not be highly insulated because the induced voltages are so small. It is not necessary to insulate the discs from the shaft because the motion of the center of the armature is almost zero, and no electro-motive-forces are induced at this point, and furthermore, as the shaft constitutes but one side of an open circuit there is no danger of currents from the discs flowing along it. Also, except in bipolar

machines, there is almost a total absence of magnetic flux at the center of the armature. If, however, the discs are of large diameter and bolts are required near the circumference to hold them together, these bolts must be carefully insulated throughout their length and under their heads, otherwise they would short-circuit the laminations and create heavy currents with consequent loss of power.

The eddy current loss is influenced by three things and is proportional to the square of each of these three quantities. It is proportional to the square of the speed, to the square of the flux density and to the square of the thickness of the laminations. To minimize these losses then, the laminations should be very thin and the flux density and speed should be kept moderately low.

Fundamental Formula for Generated E.M.F.

It will be well to consider next the fundamental formula for the e.m.f. produced in a generator armature. This e.m.f. is equal to the product of three factors, thus:

$$V = \Phi Z n.$$

V = e.m.f. in absolute units.

Φ = number of magnetic lines emanating from one pole.

Z = total number of face conductors on the circumference of the armature.

n = number of revolutions per second.

It is evident from the above that raising or lowering any one of these three quantities will raise or lower the e.m.f. induced in the same ratio. It might be supposed that as a conductor cuts the magnetic flux twice in a revolution in a bipolar field, there would be produced in a generator twice the voltage indicated by the above formula. A reference to Fig. 289, however, will show that it was necessary to generate the voltage required by the external circuit in each half of the armature winding and while each half contributes 50 amperes out of the total 100 amperes, the voltage for each half must be separately maintained. Thus, twice the specified voltage must be generated because of the two paths through the armature winding.

The e.m.f. in volts produced by a generator is as follows:

$$E = \frac{\Phi Z n}{10^8}.$$

E = e.m.f. in volts.
Φ = number of magnetic lines emanating from one pole.
Z = total number of face conductors on circumference of armature.
n = Number of revolutions per second.
10^8 = Constant to reduce the e.m.f. to practical units.

Consider this formula as it might be used in a practical machine. Suppose that a flux of 4,000,000 lines is produced across an armature which carries 200 conductors on its surface and is driven at 15 revolutions per second.

$$E = \frac{\Phi Z n}{10^5} = \frac{4,000,000 \times 200 \times 15}{100,000,000} = 120.$$

The electro-motive-force varies directly with the flux. Therefore, if the field current employed for excitation were reduced so that the flux fell to 2,000,000 lines, the voltage generated would also fall from 120 to 60. If, on the other hand, it were possible by increasing the field current to raise the flux to 8,000,000 lines, the e.m.f. would correspondingly increase from 120 to 240 volts.

If the armature instead of carrying 200 conductors had but 100, the voltage would be reduced to 60; whereas, if the winding were replaced with one having 400 conductors the voltage would be increased from 120 to 240 volts.

Finally the speed of a generator is a factor of the voltage and therefore a factor of the output. If the above machine is driven 30 revolutions per second (1800 r.p.m.) the voltage produced would be 240 instead of 120. Assuming a machine furnishing 120 volts and 100 amperes or 12 kilowatts at 900 r.p.m., the same machine could be made to deliver 240 volts and 100 amperes or 24 kilowatts at 1,800 r.p.m. The rating of the machine then depends upon its speed. Most manufacturers give three different ratings for machines built with the same size frame. At the lowest rating the machine is designated "slow speed." A higher rating is obtained at "moderate speed" and the machine has a maximum output at "high speed."

Early machines were conspicuously "high speed." Later it became a fad to build abnormally slow speed machines. Actual speeds today are determined by the particular requirements in a given case. Machines driven by reciprocating engines of the

Corliss type are generally very slow in speed. Those driven by steam turbines are exceedingly high speed.

Relation between Conductors and Voltages in Armature Windings

Direct current generators or motors of one voltage may be rewound for a different voltage by adopting the following general rule: To rewind a 220-volt machine for 110 volts, it is only necessary to replace the wire on both armature and field with a new winding consisting of one-half the number of convolutions of just twice the circular mils cross-section. Thus, if an armature contained 20 turns of No. 22 wire in each coil, designed for 220 volts, it could be rewound for 110 volts with a coil containing 10 turns of No. 19 wire. As the latter coil has twice the cross-section and contains one-half the number of turns it will occupy practically the same space as the former coil. The field coil should be replaced in a similar manner. To avoid the necessity of counting the convolutions on the field, however, a simple rule is to replace the 220 volt coils with coils which weigh the same number of pounds but have twice the circular mils cross-section. Thus, if each of the field coils of the 220-volt machine contains 3 pounds of No. 27 wire, they should be replaced with coils weighing 3 pounds each of No. 24 wire for 110 volts.

In rewinding machines of low voltage for higher voltages, difficulty may be experienced in getting the required number of turns in the slots on the armature. Thus, suppose that 10 turns of No. 19 wire exactly filled the slot on a 110-volt armature. When replacing this with 20 turns of No. 22, difficulty would be experienced because of the greater amount of insulation on the 20 turns compared with that on the 10 turns. It therefore might be necessary to leave off say 10% of the required number of turns, or 2 turns, putting 18 instead of the required 20 in the slot. The result would be that the machine would have to be driven at 10% greater speed to get the same voltage or it would give 10% less voltage at the original speed.

SECTION VIII CHAPTER IV

D. C. GENERATORS

ARMATURE CONSTRUCTION AND DESIGN

1. What three losses occur in the armature of every generator?

2. How may the I^2R loss in the winding of a generator armature be minimized?

3. How may the hysteresis loss in the core of a generator armature be minimized?

4. How may the eddy current, loss in the core of a generator armature be minimized?

5. Give the fundamental formula for the e.m.f. developed in a generator armature. Tabulate the meaning of each letter.

6. What is the effect upon the generated voltage in a machine, if the flux, number of conductors or speed is varied?

7. What is the practice among manufacturers with reference to the speed rating of generators?

8. How would the armature of a 220-volt machine be rewound for 110 volts?

9. How would the field of a 220-volt machine be rewound for 110 volts?

10. Is there any difficulty experienced in rewinding machines of one voltage or a lower voltage? Why?

11. What two difficulties may be encountered in rewinding machines of one voltage for a much higher voltage?

12. If the number of conductors cannot be placed in the slots when rewinding a low voltage machine for a higher voltage, what will be the effect upon the speed?

DIRECT-CURRENT GENERATORS

ARMATURE WINDINGS

The **front** of an armature is the commutator end. The **back** of an armature is the pulley end. A **face conductor** is one extending the length of the armature core.

A **convolution** consists of two face conductors with the end connections uniting them. A **coil** may consist of one or more

Fig. 294.

convolutions. A coil requires two **winding spaces** in the slots, to accommodate the two halves of the coil. A **slot** may contain one or more winding spaces. The **spread** or **throw** of a coil is the distance along the circumference of the armature from the outgoing conductors of a coil to the returning conductors of the same

coil. This is approximately 180 mechanical degrees on a bipolar machine, 90 degrees on a four-pole machine, etc.; in general, $\frac{360°}{p}$ = throw, where p is the number of poles in the field.

The **pitch** of a winding will be the same as the throw of a coil if the slot contains but one winding space. Fig. 294 illustrates a drum winding. expanded from the back as by the insertion of a

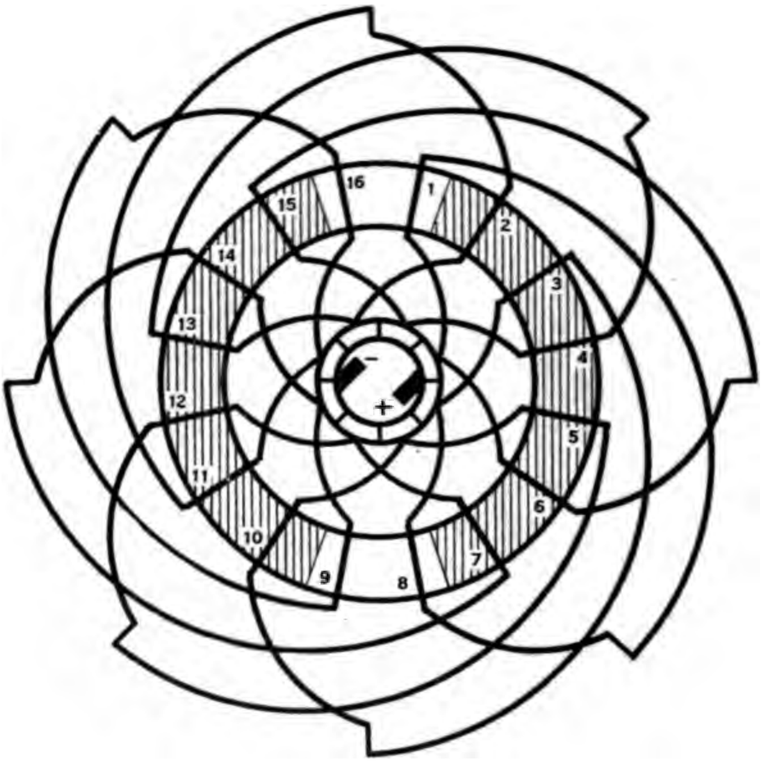


FIG. 295.

funnel. The commutator is shown at the center, with the brushes, for convenience, on the inside. The straight radial sections of the winding represent the conductors in the slots. The inside terminals show the connections to the commutator on the front, while the outside curved conductors represent the connections across the back of the armature. The shaded portions of the figure represent the sections of the armature embraced by the

pole pieces. In winding drum armatures (Fig. 294), a conductor is connected to a commutator segment, resting under a positive brush and is led back through slot No. 1, whence it passes across the back of the armature to the right of the shaft and returns through slot No. 10 and terminates on the next adjacent segment to the right of the one from which it started. This constitutes a coil and may have one or more convolutions. In this winding the ends of a coil terminate on adjacent commutator segments.

The number of winding spaces passed over on the back of an armature (and also on the front if the coil consists of more than one convolution) in connecting together the opposite conductors of a coil, is called the **back pitch** of the winding. The back pitch of a winding should preferably be equal to the total number of winding spaces divided by the number of poles. In Fig. 294 the number of winding spaces is 18 and the number of poles 2. Eighteen divided by two is nine. As the outgoing conductor in No. 1 returns in No. 10, which is thus 9 winding spaces to the right removed from No. 1, the back pitch is 9. In order that the winding may be symmetrical it is not possible to have the back pitch equal one-half of the number of winding spaces unless the number of coils is odd. As two winding spaces are required for each coil, the number of coils in this armature will be 9 and there are 9 segments in the commutator. There are always as many segments as coils. If the number of coils had been 8, an even number, with 16 winding spaces, as in Fig. 295, the back pitch would have been made one-half of the number of winding spaces plus or minus one. This is necessary in order that a symmetrical winding shall be produced and that all the winding spaces shall be uniformly occupied before the winding closes upon itself.

Referring again to Fig. 294, coil No. 1 occupying slots No. 1 and No. 10 terminates on adjacent commutator segments which are short-circuited by the positive brush. As these conductors are in the neutral gap space between the field poles, no harm results. Leaving the last end of coil No. 1, coil No. 2 starts from the same commutator segment. This cannot be placed in slot No. 2, as that must be left for the returning conductor of another coil in order to produce a symmetrical winding. But the first conductor of coil No. 2 must pass out through slot No. 3. It will be noticed that the last end of coil No. 1 comes from slot No. 10 to the

same segment from which the first end of coil No. 2 entering slot No. 3 starts. Thus the number of winding spaces passed over in connecting adjacent coils (last end of coil No. 1 to first end of coil No. 2) is called the **front pitch** of the winding. The front pitch appears only on the front of the armature and is reckoned backward from slot No. 10 to slot No. 3. It is evident that the front pitch differs from the back pitch by 2, in this case being seven. The back pitch, viewed from the front of the armature, shows an end connection passing from slot No. 1 to slot No. 10 from left to right. This direction is therefore designated as plus, while the front pitch where the conductor from slot No. 10, via the segment to slot No. 3, is from right to left is designated as minus.

The conductor that goes out through slot No. 3 returns through slot No. 12 and terminates on the next adjacent segment to the right. As commutator segments are thus being occupied from left to right, this is called a right-handed development or a progressive winding. If the order of connection to the segments were from right to left, it would be called a left-handed development or a retrogressive winding.

Coil No. 2 overlaps coil No. 1 by the space from slot No. 3 to slot No. 10. Hence, this was originally called a **lap winding.** Furthermore, as these coils constitute a series of loops, it has sometimes been designated as a **loop winding.** Coil No. 2 now terminates upon the next adjacent segment to the right and No. 3 starts from the same segment and goes out in slot No. 5, returning in No. 14; taking in the next commutator segment the coil starts in No. 7 and returns in No. 16; thence via a segment to No. 9, returning in No. 18; thence via a segment to No. 11, returning in No. 2; thence via a segment to No. 13, returning in No. 4; thence via a segment to No. 15, returning in No. 6; thence via a segment to No. 17, returning in No. 8, and the last end of this last coil connects to the same segment from which the first end of the first coil started. Such a winding is called a **closed coil** or **re-entrant winding,** because after encircling the armature the winding reenters or closes upon itself re-entrant.

There are many possible variations of drum armature windings. In general, the number of conductors must be even, although the number of coils may be even or odd.

The back pitch of a loop winding should conform approximately to the following formula:

For an armature with an odd number of coils,

$$yb = \frac{w}{p}$$

For an armature with an even number of coils,

$$yb = \frac{w}{p} \pm 1.$$

Where w = number of winding spaces.

p = number of poles in the field.

yb = back pitch of the winding.

In winding the armature, Fig. 295, which has an even number of coils, the number of winding spaces being even, the back pitch is

$$\frac{16}{2} = 8 - 1 = 7.$$

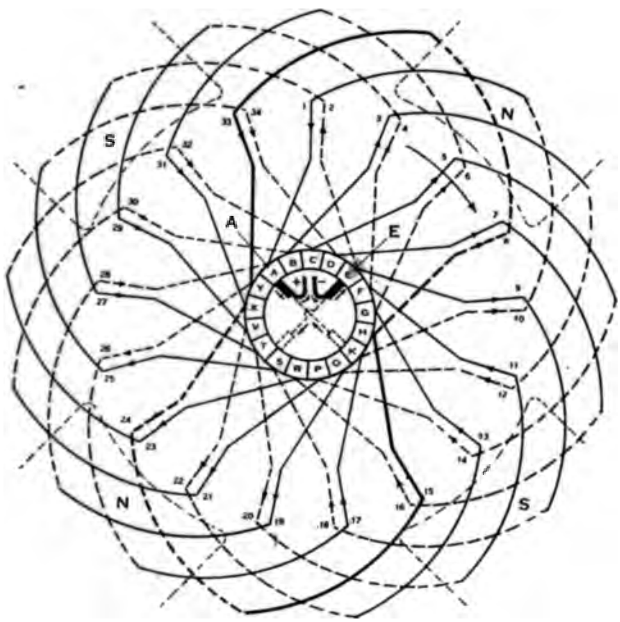


FIG. 296.—Two-layer, two-circuit drum type armature winding for 4-pole machine.

This could have been made 8 + 1, which, however, would have entailed longer end connections on the back of the arma-

ture. Hence it is preferable to make it 8 − 1. This variation of the back pitch is necessary whenever there is an even number of coils, in order that the winding may be perfectly symmetrical before it closes re-entrant.

By following the development of the winding in Fig. 295, it will be seen that it is the same as Fig. 294, except for the values of the front and back pitch. As in both Figs. 294 and 295, the front pitch always differs from the back pitch by 2. As there

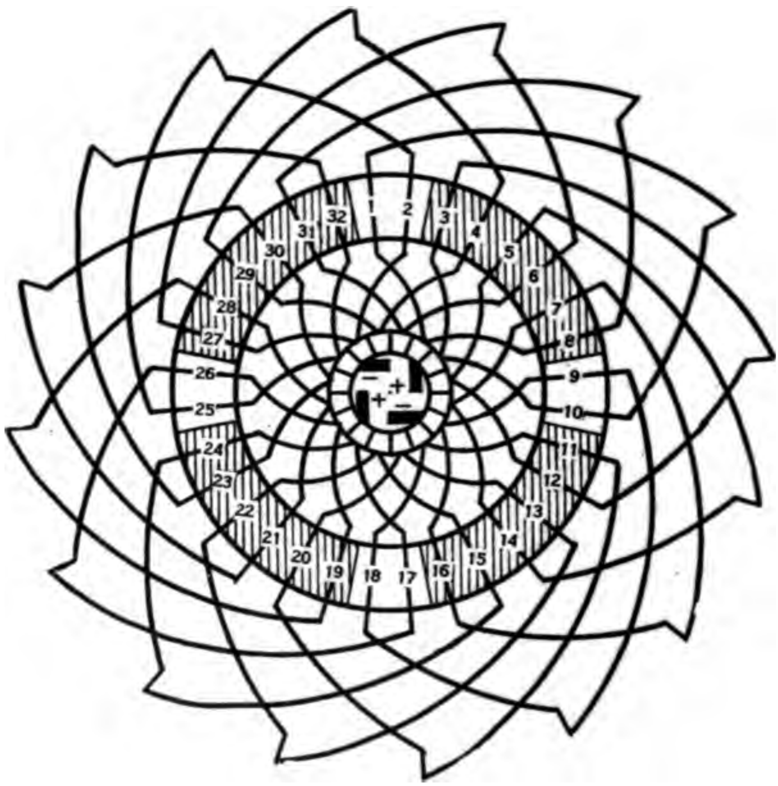


FIG. 297.—Single layer parallel drum armature for 4-pole machine.

are an even number of coils in Fig. 295 there is a coil short-circuited simultaneously by the positive and negative brushes, while in Fig. 294 there is a coil short-circuited alternately; first by the positive and then by the negative brush. There is a slight advantage in the position for short-circuiting the coil in

Fig. 294, which is exactly in the middle of the neutral gap spaces while both the coils short-circuited by the two brushes in Fig. 295 are somewhat active. The difference in commutating conditions, however, is so slight as to be unnoticed in practice.

The back pitch of a winding may differ from the values given in Figs. 294 and 295 by two or any multiple of two. Thus, in winding the first coil in Fig. 294, slots 1 and 8 instead of 1 and 10 could be used. When opposite conductors of a coil occupy slots separated from each other by less than 180 electrical degrees, it is called a **chord winding.** In such a case, however, it is important that the chord should never be less than the angle which subtends a polar face; otherwise the opposite conductors of the coil will be in front of the same pole at the same time and this would involve opposing e.m.fs. in the same coil, which would cut down the delivered e.m.f. However, a chord winding is advantageous in diminishing the demagnetizing effect of the armature on the field, provided the chord is not too short.

It is important to observe that in drum windings there is the full potential difference between adjacent conductors in the neutral gap spaces or between the top and bottom coils of a two-layer winding in the same slot. This necessitates extra care in insulating these coils, and especially the end connections where one coil crosses another on the heads of the armature. In Fig. 295 it will be noticed that the conductors occupying slots 1 and 16 lead to diametrically opposite brushes across which the whole potential of the machine is maintained. In a two-layer winding, these conductors would occupy the top and bottom of the same slot, as in Fig. 296, where conductors 1 and 2 in slot No. 1 lead to segments *A* and *E*. Hence the necessity for the extra precautions above mentioned.

In sharp contrast to this is the distribution of potentials in a Gramme ring winding where there is never a greater potential difference between adjacent conductors than the e.m.f. of one coil.

Parallel Windings

In winding a 4-pole drum armature, the throw or spread of the coil is approximately 90 mechanical degrees instead of 180 degrees.

Fig. 297 illustrates such a winding. Here, the first coil starts from the segment under the right hand upper positive brush,

enters slot No. 1, goes to the right and returns through slot No. 10, which is 9 winding spaces removed from No. 1, hence the back pitch is +9. Terminating this coil on the next segment on the right, coil No. 2 starts in slot No. 3, hence the front pitch is −7. The development of this winding is progressive and continues as in Fig. 294, until it closes upon itself re-entrant.

On armatures having four or more poles, form-wound coils are generally employed, which are shaped up as shown in Figs. 298 and 299. The end connections thus extended and avoiding the shaft, give the appearance of a barrel, hence the term barrel

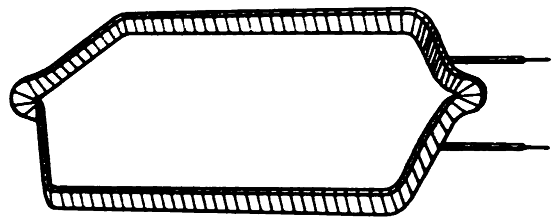


Fig. 298.

winding. This arrangement is especially adapted to two-layer windings. The two sides of the coil are set in different planes and the heads are supported by metallic flanges extending from the armature core.

When a winding encircles an armature once on either a bipolar or multipolar machine occupying all winding spaces and commutator segments, and then closes upon itself re-entrant, it is designated as a single parallel or multi-circuit winding. The

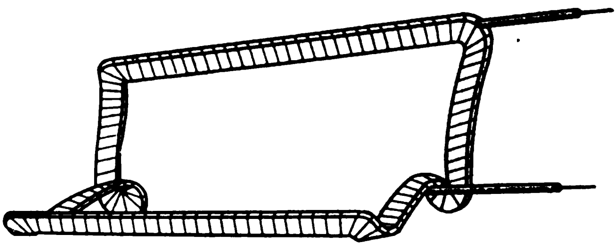


Fig. 299.

winding is also said to be single re-entrant. There will be one brush on the commutator for every pole in the field, and the location of any brush should be on a segment leading into the winding at a point midway between adjacent poles. (See Fig. 297.)

In order to deliver a large current from an armature without using excessively heavy wire, double windings are sometimes

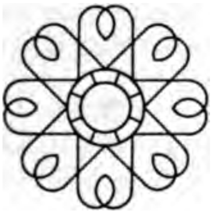


FIG. 300.

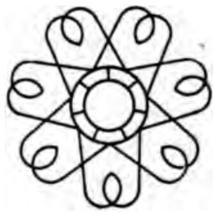


FIG. 301.

employed. These two windings are interlaced, that is to say, one winding occupies a set of winding spaces alternately spaced between those occupied by the other winding. The brushes must be broad enough to span two or three segments all the time, and thus place these windings, which are otherwise insulated from each other, in multiple. This is called a double parallel winding. As each winding may have any number of coils, double parallel windings may have any even number of coils. Such a winding is illustrated in Fig. 300.

A single re-entrant double winding may be constructed with an odd number of coils, as shown in Fig. 301. Here, after one winding completely encircles the armature, occupying alternate winding spaces and commutator segments, instead of closing upon itself, enters the second winding and encircles the commutator again before closing upon the first end of the first coil, re-entrant. Therefore it is a **singly re-entrant double parallel winding.** Broad brushes place these two windings in multiple, as before. In both of these cases there are twice as many paths between the positive and negative brushes as there are poles in the field.

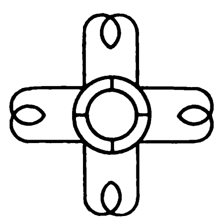


FIG. 302.

To recapitulate: Fig. 302 represents a single parallel, multi-circuit winding which is singly re-entrant. Here there are as many paths between positive and negative brushes as there are poles in the field. Fig. 300 is a double winding, doubly re-entrant with an even number of coils. There are twice as many paths between positive and negative brushes as there are poles in the field and the brushes must

always cover at least two segments. Fig. 301 is a double winding which is singly re-entrant, having an odd number of coils and segments. Here, as in Fig. 300, the brushes must span at least two segments. In practice, there is no difference in the operation of armatures shown in Figs. 300 and 301.

When the bearings of an armature shaft wear on the bottom, the armature settles. If a four-pole field is employed this results in a shortening of the lower air gaps and a lengthening of the

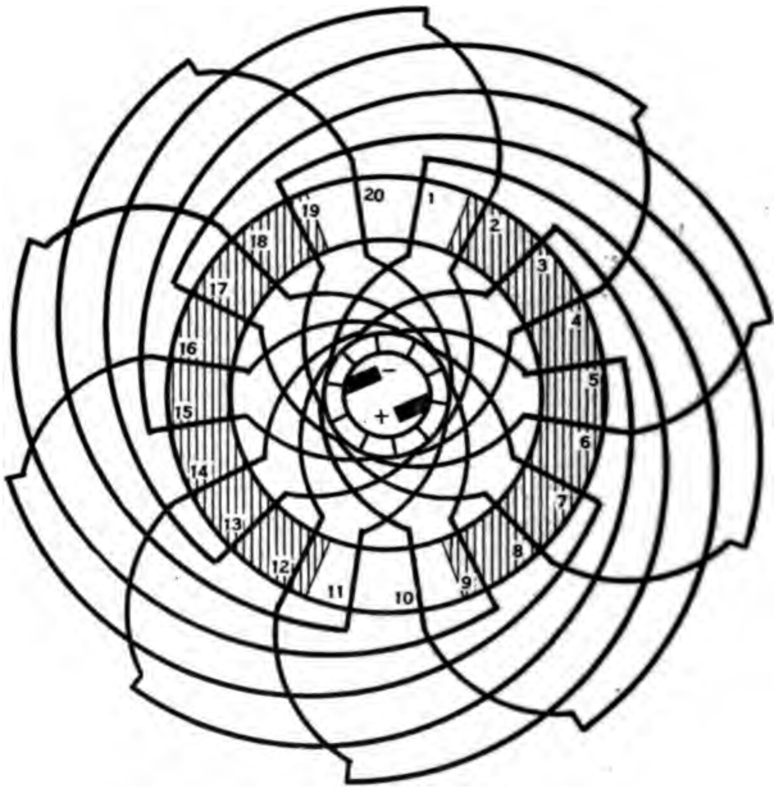


FIG. 303.

upper air gaps. This causes a weakening of the flux from the upper poles and a strengthening of the flux from the lower poles. Unequal electro-motive-forces are then generated in different parts of a parallel winding. The result is, the machine sparks badly at the brushes and groans as it operates, due to the

fact that it is electrically and magnetically unbalanced. This is called **bucking.** The remedy is to cross-connect the commutator segments on a four-pole machine connecting each segment permanently by a conductor to one diametrically opposite. This necessitates an even number of coils on the armature; otherwise there would be one segment left over when cross-connected. These cross-connections form equalizing conductors which transfer the current caused by unequal voltages from one segment to the one opposite. As opposite segments are thereby

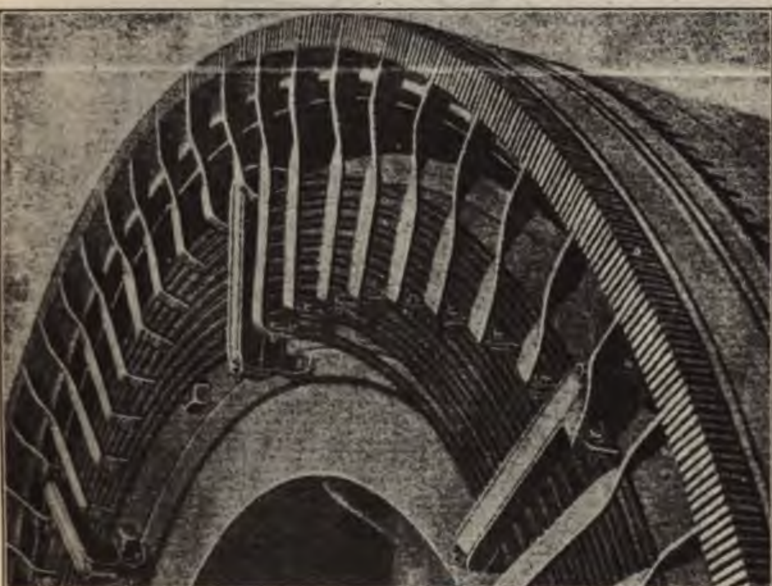


FIG. 304.—Armature of General Electric D. C. Railway generator, showing "balancing ring."

held at the same potential, sparking from the above cause is prevented. As these cross-connections are cumbersome on the commutator end, a better method more frequently resorted to is the use of balancing rings on the back of the armature. Fig. 304 shows the application and arrangement of the balancing rings on the back of the armature. The number of these rings employed is experimentally determined. All points of the winding which are at one potential are connected to one ring, the number of points being equal to the number of pairs of poles. These rings are extensively used on rotary converters and on large direct-current armatures.

Series Windings

Referring to Fig. 303, if the end connection from the first coil is taken from the upper segment under the negative brush, passed to the right, thence out through slot No. 1 and again to the right around the back of the armature and returned in slot No. 10, it will come up to the next segment below the one from which the coil started, and it will be observed that both front

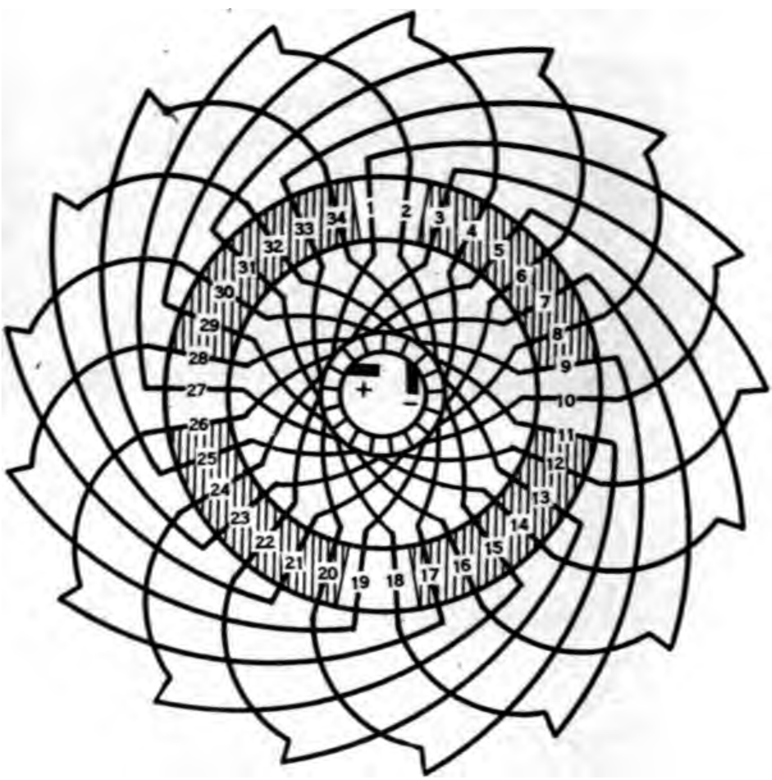


Fig. 305.—"Two-circuit" or "series" armature winding.

and back pitches are given the same direction and the armature instead of rocking back and forth, as it is wound, is always turned the same way. Giving both pitches the same direction does not produce any different effect in a bipolar winding from that obtained when they have opposite directions, and it is simply determined by which side of the armature shaft the

conductor passes in completing the end connections of a coil on the back of the armature. Giving both pitches the same direction in a multipolar winding, however, changes it from a parallel or lap, or multi-circuit winding, to a **series** or **wave** or **two-circuit winding.** A two-circuit winding is shown in Fig. 305. Here a coil starts from the segment under the positive brush, passes into slot No. 1 across the back of the armature about 90 degrees,

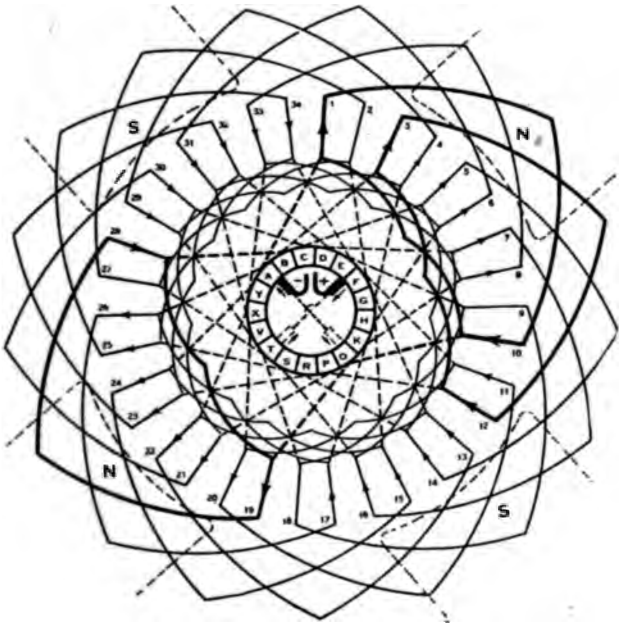


FIG. 306.—"Two-circuit" or "series connected" armature winding employing coils instead of bars.

returns through slot No. 10 to a commutator segment, thence into slot No 19, returning through slot No. 28 and thence to the next segment from which the series started. It will be observed that the coil occupying slots No. 1 and No. 10 is in series with coil occupying slots No. 19 and No. 28. This plan of connecting up two coils in series and connecting the "set of series" to adjacent segments is continued throughout the winding. The result is that there are but two paths through the winding, regardless of the number of poles in the field, and but two brushes are required on the commutator. If there were six poles instead of four, there would be three coils in series before connecting to adjacent seg-

ments. In other words, in a series winding, all of the coils in the same relative positions under like poles are connected together in series.

The balancing rings prevented bucking by placing sections of the armature winding, normally at the same potential, **permanently in parallel.** The series winding prevents bucking by placing sections of the winding under similar poles **permanently in series.** The voltage of a series winding is greater than that of a parallel winding in proportion to the number of pairs of poles in the field.

The formula for the e.m.f. generated in a parallel-wound armature is

$$E = \frac{\Phi Z n}{10^8}.$$

The formula for the e.m.f. generated in a series winding is

$$E = \frac{\Phi Z n P}{10^8}.$$

Where E = e.m.f. generated.
Φ = Magnetic flux per pole.
P = Number of pairs of poles in field.
Z = Number of armature conductors.
n = Number of revolutions per second.

If a four-pole armature containing a given number of conductors is connected as a parallel winding so as to deliver 20 amperes at 110 volts, the same armature connected as a series winding with the same number of conductors would give 10 amperes at 220 volts. It is therefore evident that the e.m.f. of a series winding is equal to P times the e.m.f. of a parallel winding for the same number of armature conductors, the current delivered, varying inversely with the voltage for a given size armature, the power being the same in the two cases.

The series winding is commonly used on street railway motors because of its adaptability to the relatively high voltage of the system and its freedom from sparking troubles when the armature wears down in its bearings, and the fact that only two sets of brushes are required and these can be placed on top where they can be readily inspected from above.

A single series winding is one in which a series of "$\frac{p}{2}$ sets of

coils" encircles the commutator any number of times, necessary to include all coils and slots. The terminals of each set of "$\frac{p}{2}$ coils" must be connected to adjacent commutator segments. The single series winding is the commonest two-circuit winding employed. The number of coils possible in such a winding is

$$C = \frac{p}{2} y \pm 1.$$

p = number of poles in field.

y = the connecting pitch, that is, the number of commutator segments passed over between the terminals of the coil.

C = number of coils on armature.

In Fig. 305, the conductor in slot No. 10 connects to the ninth commutator segment removed from the one on which the conductor in slot No. 1 terminates. Therefore the applictaion of this formula is

$$\left(\frac{4}{2} = 2 \times 9\right) - 1 = 17 \text{ coils occupying 34 winding spaces.}$$

Fig. 306 shows a single layer series winding, that is, one-half of a coil completely fills a slot and may consist of a bar, as in

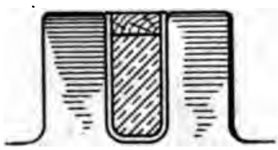


FIG. 307.—Bar winding.

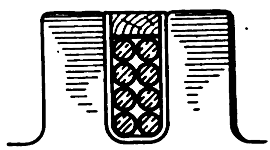


FIG. 308.—Coil winding.

Fig. 307, or a coil, as in Fig. 308. If a bar is employed, the coil. has but a single turn and the end connections are as in Fig. 309

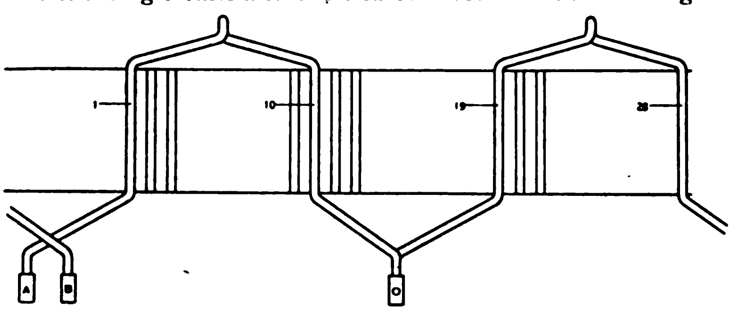


FIG. 309.—End connections for "two circuit" or "wave" wound armature.

If it is a coil of several convolutions, the end connections are as in 310. This winding is identical with the parallel winding

shown in Fig. 311 except in regard to the end connections to the commutator. In Fig. 311 each coil forms a loop as in Fig. 312 and its terminals are connected to adjacent segments. In Fig. 306 and Fig. 309 the winding progresses in a series of zigzag lines or waves, hence it is called a **wave** winding. While Fig. 311 and Fig. 312 is called a **lap** or **loop** winding. It is preferable,

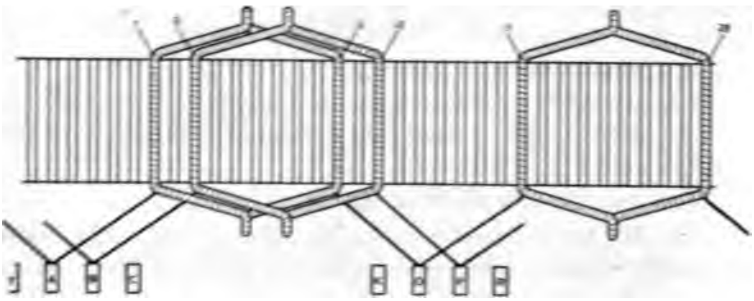


FIG. 310.—Connections of adjacent coils on wave wound armature.

however, to designate the **lap winding** as a **parallel** winding and the **wave winding** as a **series winding.**

The relation between the number of poles, the pitch and the number of coils for a series winding, which results from the application of the series formula should be considered.

A few possible variations are as follows:

$$C = \frac{4}{2} \times \begin{cases} 7 \begin{array}{l} +1 = 15 \text{ coils} \\ -1 = 13 \text{ coils} \end{array} \\ 8 \begin{array}{l} +1 = 17 \text{ coils} \\ -1 = 15 \text{ coils} \end{array} \\ 9 \begin{array}{l} +1 = 19 \text{ coils} \\ -1 = 17 \text{ coils} \end{array} \end{cases}$$

Using a back or connecting pitch of 7, 8 or 9 plus or minus 1, shows that an odd number of coils will always be obtained if the number of poles, four, divided by two, is an even quantity. Therefore, when $\frac{p}{2}$ is **even,** C must be **odd.** Four pole railway motors, using a series winding, will therefore require an odd number of coils. A certain manufacturer, having conveniently available an armature adapted for an even number of coils, was obliged to place in one pair of winding spaces a dead coil, the ends of which were taped up and not connected to the commutator, in order to satisfy the above formula.

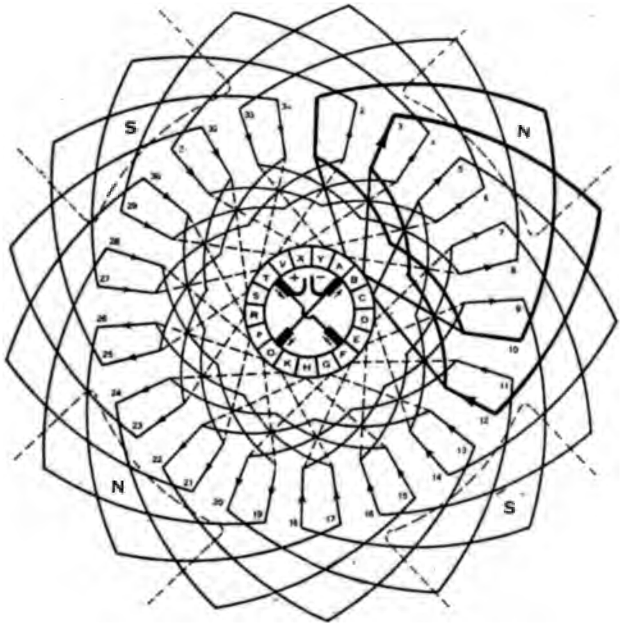


FIG. 311.—"Multi-circuit" bar winding.

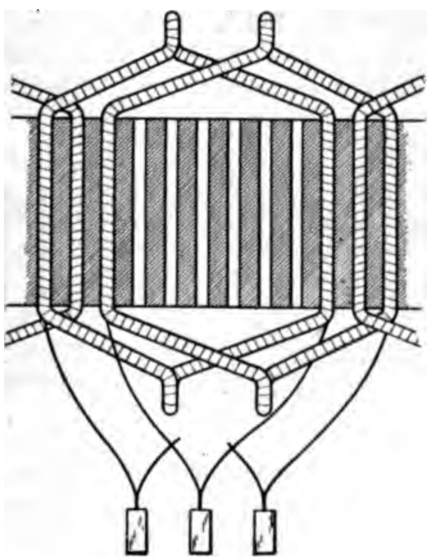


FIG. 312.

Applying the foregoing principle to a 6-pole machine the following are some of the possible variations:

$$C = \frac{6}{2} \times \begin{cases} 7 \begin{array}{l} +1 = 22 \\ -1 = 20 \end{array} \\ \hline 8 \begin{array}{l} +1 = 25 \\ -1 = 23 \end{array} \\ \hline 9 \begin{array}{l} +1 = 28 \\ -1 = 26 \end{array} \end{cases}$$

Here the quotient obtained by dividing the number of poles by 2 is **odd.** Then, whether the number of coils required shall be **even** or **odd** depends upon the **pitch,** for when $\frac{p}{2}$ is **odd,** C is **even** if y is **odd.** Thus, if the back or connecting pitch **were** 9, 28 or 26 coils would satisfy the formula for if $\frac{p}{2}$ is odd, C is **even** if yb is **odd.** But if the connecting pitch were 8, 25 or 23 coils would satisfy the equation, for y then being **even,** C is **odd.** Under all circumstances, for a single series winding, the number of coils must satisfy the equation

$$C = \frac{p}{2} \times y \pm 1.$$

Referring back to Fig. 296 it will be observed that there are but two paths through this winding and that only two brushes are required to collect the current. Nevertheless if the current

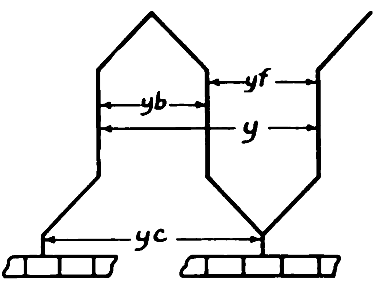


FIG. 313

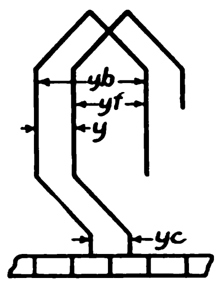


FIG. 314

collecting capacity of the two brushes is not sufficient, other brushes may be placed in the dotted position shown and connected in parallel with the ones diametrically opposite, without altering the result. It is a two-layer winding in which one half of each coil

occupies the bottom of a slot, shown in dotted lines, the other half shown in solid lines occupies the top of another slot. These two-layer windings are quite commonly used for both series and parallel connected armatures.

The distance between the outgoing conductor of one coil and the outgoing conductor of the next coil connected to it is called the **total winding pitch.** It is designated by the letter y. If yb equals the back pitch and yf the front pitch then y equals the total winding pitch. This is generally the same as the commutator pitch, yc. Fig. 313 illustrates these pitches for a wave winding and Fig. 314 for a lap winding.

In general, it may be stated that the commutator pitch, yc, on either winding is equal to the algebraic sum of the front pitch, yf, and the back pitch, yb.

When the throw of a coil is exactly equal to $\frac{360°}{p}$ or 180 electrical degrees, it is said to be a **full pitch coil.** This throw or spread of the coil is also known as the **pole pitch.** If the throw is less than $\frac{360°}{p}$, it is said to have a **fractional pitch.** Such a winding is often designated as a **short pitch** or short chord winding.

In the case of Fig. 296, which is a 4-pole, 2-layer winding with 17 slots containing 34 winding spaces and 17 coils and 17 commutator segments, the back pitch, yb, is 9 and the front pitch, yf, is 7. The formula for the commutator pitch in such a winding is

$$yk = \frac{yf + yb}{2} = \frac{7 + 9}{2} = 8.$$

The first end of conductor 1 in the top half of the first slot is connected to segment A, while the last end of this coil, occupying winding space 10 in the bottom of another slot, terminates on segment K, which is the eighth segment removed from A, thus satisfying the requirements of the commutator pitch called for in the formula. Thus, in a 4-pole machine, the last conductor of one coil, and the first conductor of another coil which lies under another pair of poles, are connected to one commutator segment. The last end of the second coil is connected to the commutator segment y, adjacent to the one from which the first end of the first coil was connected. Thus there are two coils connected in series with their outgoing conductors under different north poles and their

returning conductors under different south poles. A wave winding thereby results in producing a series or two-circuit winding.

Where formed coils are employed, one half of each coil may be placed in the bottom of each slot, the first end of each coil tagged respectively, +1, +2, +3, etc. The last ends of these coils are correspondingly tagged −1, −2, −3. If the armature is to be connected as a parallel winding, each coil must terminate on adjacent segments. If a two-layer winding is desired, Fig. 308 shows how simply the connections are arranged. Taking, say, the right-hand half of each coil, and placing in the bottom of its

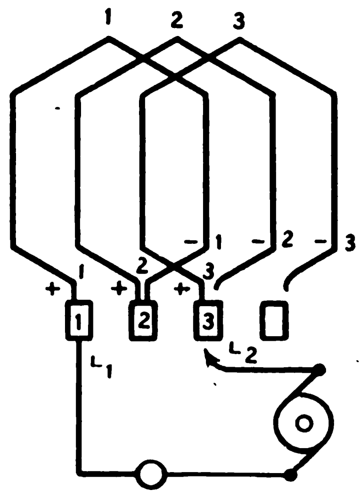


FIG. 315.

proper slot, as many coils as slots will be required. The left-hand half is then folded down to occupy the top of a slot separated from the one in which the other half of the coil is placed by the proper throw. Selecting two segments approximately midway between the spread of the coil, connect the plus end of coil No. 1 to segment No. 1. The plus end of No. 2 should be connected to segment No. 2, the plus end of coil No. 3 to segment No. 3 and so on until the first end of every coil is connected to one commutator segment. Every segment will now have one wire connected to it. If no system of identification has been used the following method may be employed for identifying the proper coils: Thus taking the two ends of a testing circuit, *L*-1

and *L*-2, Fig. 315, coming from a generator in series with a lamp, apply *L*-1 to segment No. 1 and test with *L*-2 until the lighting of the lamp indicates the minus end of coil No. 1. This is then connected to segment No. 2. Leaving *L*-1 in the same position, *L*-2 is now used to explore for the minus end of coil No. 2. This in turn should be brought down to segment No. 3, continuing to test for the negative terminal of each succeeding coil. All of these ends in proper order may be connected to their segments until the winding closes upon itself re-entrant.

Should a series winding instead of parallel winding be desired, the two ends of each coil would connect to segments approximately 180 electrical degrees apart, instead of connecting to adjacent segments, the coils thus thrown in series under like field poles terminating on adjacent segments.

The difference between a parallel and a series winding may usually be distinguished by inspection. If the end connections of a coil or face conductor on the front and back of an armature both extend the same way as in Fig. 316, it is a parallel winding.

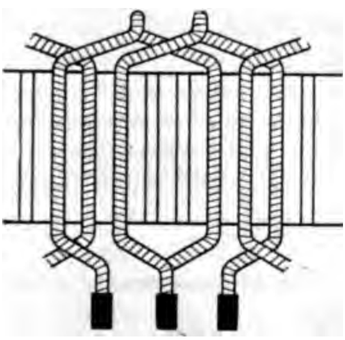


Fig. 316.

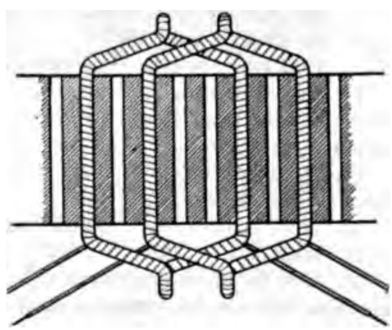


Fig. 317.

If, however, the end connections as they are viewed from the face conductor, extend opposite ways, as in Fig. 317, it is a series winding. Care should be taken to regard the end connections leading from the end of one coil to the end of another coil on the front of the armature and not the end connections constituting the turns of a single coil, which would be misleading.

SECTION VIII CHAPTER V

D. C. GENERATORS

ARMATURE WINDINGS

1. Define the following terms used in armature winding: front of armature, back of armature, face conductor; convolution; coil.
2. What is meant by the "spread" or "throw" of a coil? How is it expressed?
3. What should be the spread of a coil for any machine?
4. What is meant by the "back pitch" of an armature winding?
5. What is meant by the "front pitch" of an armature winding?
6. Define a lap or loop winding.
7. What is a closed coil or re-entrant winding?
8. What is a parallel or multi-circuit winding?
9. What is a chord winding? What are its advantages and disadvantages? What is the minimum throw for a chord winding?
10. What is a double armature winding? What are its advantages?
11. How many paths are there between brushes of opposite polarity through a parallel armature winding?
    (*a*) In a two-pole field?
    (*b*) In a four-pole field?
    (*c*) In a six-pole field?
    How many brushes does each armature require?
12. Just where should brushes be located with respect to the windings? How far apart must brushes of similar polarity be placed on the commutator in a multipolar machine with a four-pole field and a parallel armature winding?
13. What is meant by "two-circuit" armature winding? How many brushes does it require?
14. What is meant by a "series" armature winding?
15. What is a "wave" winding?
16. How far apart must brushes be placed on the commutator of a 4-pole machine with a series armature winding?
17. What is the formula for the e.m.f. generated in a parallel wound armature? What is the formula for the e.m.f. generated in a series wound armature?
18. What is the formula for the number of coils which must be employed on a series-wound armature?
19. Under what conditions must an odd number of coils be employed on a series-wound armature?
20. Under what conditions may an even number of coils be employed on a series-wound armature?
21. What restrictions are there upon the number of coils which may be employed on a parallel-wound armature?
22. What is meant by a "full pitch" winding? A fractional pitch coil?
23. What is meant by the "winding pitch" or the "commutator pitch?"
24. State the formula for the "connecting pitch" in a series winding.

DIRECT-CURRENT GENERATORS

ARMATURE REACTIONS

A generator armature may be considered in two ways, first, as a source of e.m.f. and second, as a source of magnetism. The various ways in which e.m.fs. are generated, the manner of placing the coils and the connections to the commutator have been explained. These effects may be better understood by considering the armature winding of a bipolar machine as being similar to a multiple-series arrangement of batteries, as shown in Fig. 318. Here the different cells may be used to represent individual coils. The voltage of each coil in a generator depends upon its position in the field. The coils nearest the top and bottom generate very little electro-motive-force because they cut the flux obliquely while those in the center of the field cutting squarely across the magnetic lines generate a maximum e.m.f.

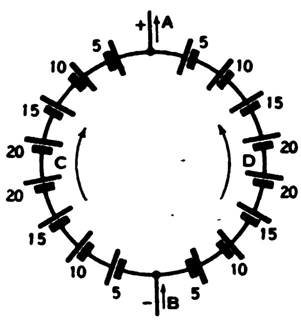


FIG. 318.

The total e.m.f. delivered at the terminals *A*-*B* will be the sum of the e.m.fs. of the separate cells or coils on one side. The sum of the voltages shown in the figure would be 100. While the voltage in adjacent coils will vary, the current is the same in all, for they are in series. If, then, terminals *A*-*B* are to deliver 100 volts and 100 amperes, the portion *C* must contribute 100 volts and 50 amperes, while the portion *D* must likewise contribute 100 volts and 50 amperes.

Next, consider the armature as a source of magnetism. Assuming for simplicity a ring winding, suppose the magnetizing effect of the current flowing through one-half of the armature is as pictured in Fig. 319. A north pole would be produced at the top and a south pole at the bottom. As the current flows through both halves of the winding at the same time, the result is as shown in Fig. 320. Here, a consequent south pole is produced where the current enters the winding and divides, and a conse-

quent north pole produced where the current leaves the winding at the top. The magnetic field produced by this current is shown in Fig. 321. The lines of force in the main emanate from one side of the ring and return through space to the other side.

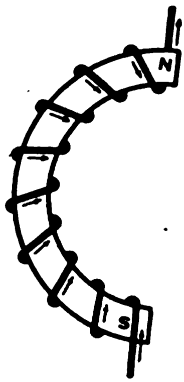


FIG. 319.

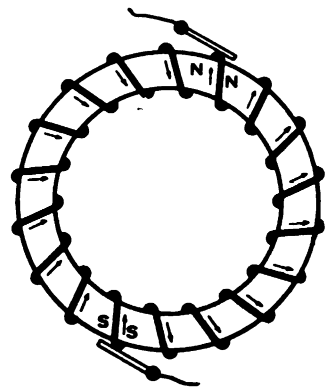


FIG. 320.

Some few leak across internally. The armature, therefore, becomes an electro-magnet with a tendency to produce a magnetic field in proportion to the current flowing through its windings. It

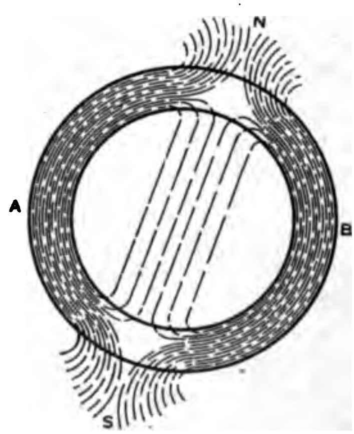


FIG. 321.

does not matter whether the armature is ring wound as in Fig. 320, or drum wound, as in Fig. 322. In both cases the conductors on the left half carry current toward the observer, and those on the right

away from the observer. The magnetic field resulting from the ring winding, shown in Fig. 320, will be identical with the field resulting from the drum winding shown in Fig. 322.

Now consider the magnetic effect of a current in an armature winding when the field is not energized. Thus, in Fig. 322, assume a current from some external source led into the winding through brushes placed in line with the points *A*-*B*. No matter what the method of winding or connection, the result will be that all the conductors on the side *A*-*C*-*B* will carry current in one direction and those on the opposite side, *A*-*D*-*B*, in the reverse direction. A circle with a dot in the center will represent

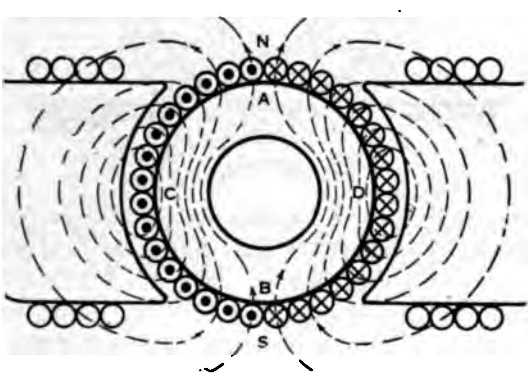


FIG. 322.

the pointed end of an arrow and pictures current flowing in a wire toward the observer. A circle with a cross in it pictures the feathered end of an arrow carrying current away from the observer. Blank circles represent idle conductors carrying no current. Thus, in the figure, the field coils are shown to be dead, while the armature is carrying a current. The magnetic field resulting will be in the direction shown. Lines of force will emanate from the top of the armature and diverge, cross the field poles perpendicularly and converge at the bottom, re-entering the armature at the south pole.

Next, consider the effect of introducing a current into the field winding while the armature carries no current. The direction of the current in the field is shown in Fig. 323 and the blank circles surrounding the armature show these conductors to be idle. The magneto-motive-force of the field windings will pro-

duce a flux which is uniformly distributed across the pole face as shown. When a current flows in both field and armature the conditions shown in Figs. 322 and 323 occur simultaneously. The armature tends to maintain a perpendicular flux and the field a horizontal flux. It is a well known fact that two fluxes cannot be maintained at right angles to each other.

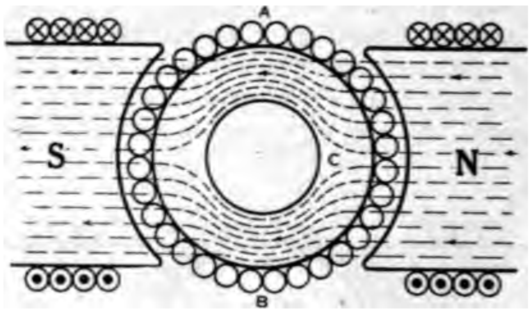


FIG. 323.

When two magneto-motive-forces operate in the same region but at an angle one to the other the direction of the field is a resultant of the two magneto-motive-forces. Fig. 324 illustrates the result of superimposing the magneto-motive-force shown in Fig. 322 on Fig. 323. Here the magneto-motive-force of the armature

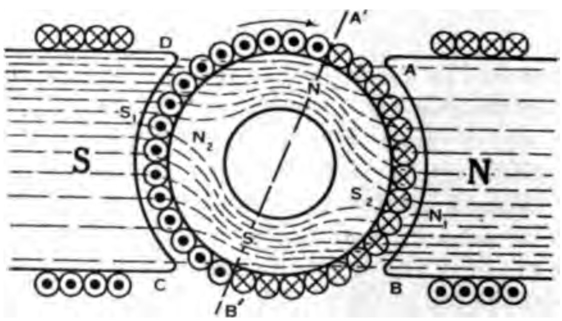


FIG. 324.

tending to produce a north pole at the top, reacts on the pole tip, A, forcing the flux away from this point, while it attracts the flux to the pole tip B, concentrating it there. The same effect is noticed on the other side of the armature, where it reacts on the pole tip C, forcing the flux away from this point and attracting

it to the tip D. Therefore, the uniform flux distribution shown in Fig. 323 is disturbed. It is weakened at A and C, Fig. 324, and strengthened at B and D. The bulk of the lines of force from the field pole N are not permitted to enter the armature at the center of the pole, but are crowded down to the position N_1. The lines of force which would enter the armature at C in Fig. 323 are not permitted to do so, but are compelled to enter at the point S_2, Fig. 324. These lines emerge from the armature at N_2 and enter the field pole at S_1 instead of at S.

As a coil terminates on adjacent segments, a short circuit results as the brush bridges these segments. To prevent an excessive current flowing in this short circuit, there must be practically no lines of force cut by this coil at this time. Hence

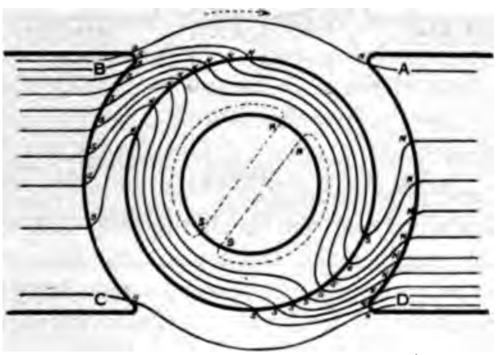


FIG. 325.

the brushes are placed where they will bridge the coil, while it is passing parallel to the flux, in the middle of the gap space.

The normal position for the brushes, if the field were not distorted, would therefore be at A-B, Fig. 323. The conductors at A-B have reached the top and bottom of the field and are about to reverse their direction of cutting. In Fig. 324, however, the field has been distorted into the direction N_1, S_1. In order that the brushes may short-circuit a coil in the neutral gap, they must be placed where they are squarely perpendicular to the field. They must, therefore, stand on the line A':B'.

It does not require power to generate an e.m.f. for there is no reaction of the armature on the magnetic field except through the magnetic effects of the currents delivered. Thus, Fig. 323 might represent an armature delivering full voltage but no

current, consequently absorbing no power and producing no distortion of the magnetic field. Fig. 325 represents in an exaggerated degree the effects of armature reacton. Here the field pole tip, A, has the magnetism practically neutralized in it

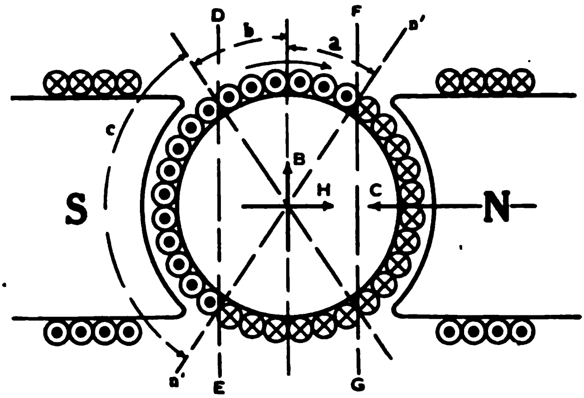


FIG. 326.

while the tip D is highly saturated. Similarly, the flux is destroyed at C and piled up at B.

The result of advancing the brushes in Fig. 324 to the position A'-B' now resolves the magneto-motive-force of the armature into two components, one a cross-magnetizing belt, represented in Fig. 326 by the conductors D-E carrying current toward

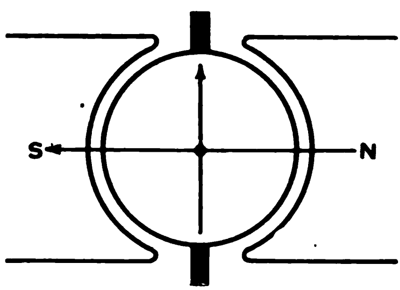


FIG. 327.

the observer, while the conductors F-G carry this same current away from the observer. These conductors produce a magneto-motive-force in the direction of the arrow B. The main field magneto-motive-force is in the direction C. The conductors D-F carry current toward the observer, which returns through the

conductors *E-G*. This represents a demagnetizing belt in the direction of the arrow, *H*. The cross-magnetizing belt tends to distort the magnetic field. The demagnetizing belt tends to weaken the magnetic field. This is shown more completely in Fig. 327. Here the relative direction of the armature and field magneto-motive-forces are pictured by arrows. Fig. 328 shows a vector diagram of these conditions. Here *O-A* represents by its length and direction the magnitude and direction of the field magneto-motive-force while *O-D* represents the armature magneto-motive-force. Thus, two magneto-motive-forces brought to bear upon the same area produce the resultant flux *O-E*. Because of this distortion of the magnetic field, the brushes must be advanced to the position shown in Fig. 329. The armature's magneto-motive-force, as now shown by the arrow, is partly against the field's magneto-motive-force. The corresponding vector is Fig. 330. Here *O-A* is the field m.m.f. as before. The armature's m.m.f., *O-D*, is in the direction of the new brush position. This may be resolved into two components, *O-F*, a cross-magnetizing force,

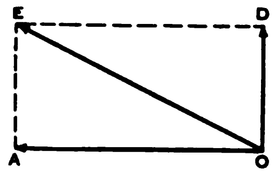


FIG. 328.

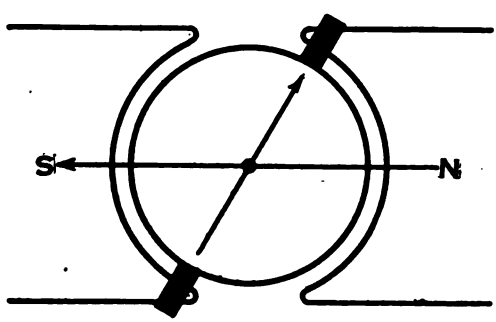


FIG. 329.

and *O-G*, a demagnetizing force. The latter is exactly opposed to the field. The resultant flux is now due to the combination of the field m.m.f., O-*A*, and the armature's m.m.f., *O-D*. A parallelogram constructed on these two components gives for the resultant flux the direction and magnitude *O-E*. It will be observed that *O-E* is distorted through a greater angle than the corresponding flux in Fig. 328, and in addition, the length of the

line O-E in Fig. 330 is less than before, indicating a smaller actual flux.

The effects of armature reaction may then be summed up as follows: An armature generating an e.m.f., but delivering no current, produces no reaction or disturbance of the magnetic field. It therefore absorbs no power (except that required for core losses).

When an armature delivers current its magneto-motive-forces react on the field flux and distort it in a generator in the direction of rotation. This brings the short-circuited coils under the brush into an active field. This results in sparking at the brushes, which necessitates shifting the brushes in the direction of rotation to a point where sparking disappears. This adjusting of the brushes resolves the armature magneto-motive-force into two components, one cross-magnetizing and the other demagnetizing. The latter weakens the field and results in still further distortion. This necessitates advancing the brushes still further to overtake the neutral line. If the field is too weak the armature reaction will distort it so far that no position can be found where commutation can be obtained without sparking.

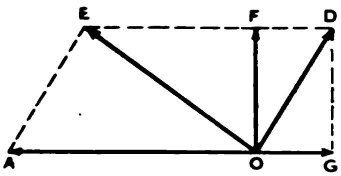


Fig. 330.

It is therefore important in machines designed for constant potential, to employ a relatively high field magneto-motive-force which will establish a high flux density in the field poles, so that these poles will be pre-empted for field magnetism and highly saturated. The armature should be relatively weak as an electro-magnet so as to produce comparatively slight reaction on the field flux. The field distortion will then be small and the brushes need be advanced but very little. These things will contribute to sparkless commutation.

SECTION VIII CHAPTER VI

DIRECT-CURRENT GENERATORS

ARMATURE REACTIONS

1. Sketch a Gramme ring armature winding for a bipolar field. If the output is 110 volts and 80 amperes, indicate approximately the voltage and current which each of the various coils contribute.

2. Sketch an armature in a bipolar field. Show the flux distribution when the armature carries no current but when the field is energized.

3. Sketch an armature in a bipolar field with the brushes in proper position. Sketch the flux distribution when the armature carries current but when the field is dead.

4. Sketch an armature in a bipolar field with the brushes in proper position. Indicate direction of rotation. Show direction and distribution of flux when field and armature are both energized.

5. If the brushes of a generator are given a forward lead, what is the effect upon the field magnetism? Explain fully.

6. Sketch an armature winding with the brushes in the proper advanced position. Lay off the cross-magnetizing belt and the demagnetizing belt.

7. If the brushes are at right angles to an undistorted field what proportion of the total armature ampere-turns are in the cross-magnetizing belt and what proportion are in the demagnetizing belt?

8. If the brushes are advanced 90 degrees what proportion of the armature ampere-turns are in the cross-magnetizing belt and what proportion are in the demagnetizing belt?

9. What precautions should be taken in the original design and subsequent operation of a generator in order that the objectionable results of armature reactions may be avoided.

10. What are the principal results of armature reaction in a generator?

DIRECT-CURRENT GENERATORS

CAUSES OF SPARKING; REMEDIES

There are two classes of sparking troubles at the commutator of direct-current machines. First, those which are inherent, due to **defective design.** Second, those due to **operating causes,** which may be remedied. Consider first those due to the inherent causes. In Fig. 331 is pictured, for convenience, a ring winding,

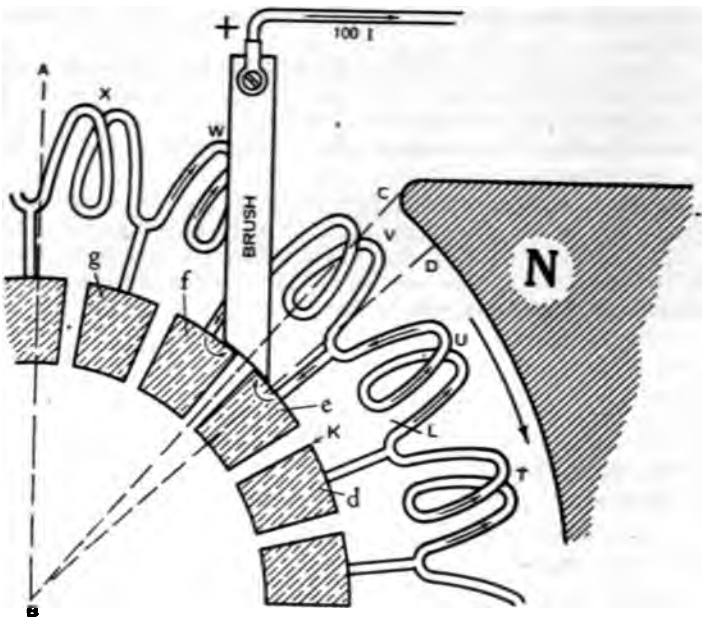


FIG. 331.

although a drum winding will produce the same results. If the brush is collecting 100 amperes it may be assumed that 50 amperes comes from the left section, embracing coils, W, X, etc., while 50 comes from the right, including coils V, U, T, etc. In the position shown, the coil V is short-circuited by the brush and is about to be transferred from the position V to the position U. In the minute fraction of a second while it is on short circuit, it is necessary that the current of 50 amperes flowing in

one direction shall be slowed down to a standstill, reversed, and brought up to 50 amperes in the opposite direction. Now it is impossible to instantly stop, start or reverse the current in a coil, because of the self-induction that is encountered. When the coil *W* reaches the position *V*, the 50 amperes flowing in it slows down to approximately 40 amperes. The attempt of the current to fall (due to the cessation of the voltage in this coil as it reaches the neutral position in the field where it is cutting no lines of force), is now opposed by an e.m.f. of self-induction due to the collapse of the flux about the coil as the current decreases. This e.m.f. of self-induction sustains the current and it may be assumed that, at the instant pictured, the current has fallen to only 40 amperes. If the brush is made of copper leaves of low resistance, no appreciable change in contact resistance between the brush and the segment *e*, takes place as the area of contact between these two decreases. The 50 amperes from *W* divides, 40 continues to flow through *V*, while the remaining 10 comes down to the segment *f*. The 40 amperes from *V* combines with the 50 from *U* and passes into the segment *e*. At the moment this segment breaks from the tip of the brush this entire current of 90 amperes must be ruptured. A spark will therefore be produced between the trailing edge of the segment *e* and the brush, as the current in *V* cannot be instantly stopped and reversed.

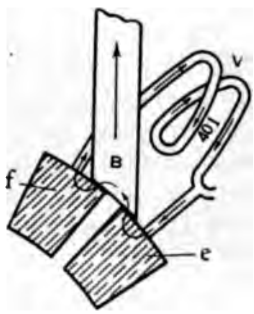


FIG. 332.

If a high resistance carbon brush is substituted for the copper one, this sparking will be lessened if not entirely prevented. Under these conditions, as the segment *e* passes out from under the brush, and the area of contact between the two diminishes, the contact resistance increases. This causes an increasing fall of potential between the segment *e* and the brush. This rising potential drop is impressed upon the coil *V* in shunt with the segment *e*, and the brush *B*, as shown in Fig. 332. This increasing resistance between the segment *e* and brush *B* causes the current from *U* to try to take the alternative path through *V* in the opposite direction to the current flowing therein and out by the segment *f* to the heel of the brush *B*. This tends to

gradually diminish the 40 amperes flowing in V, and may reduce it to zero, then reverse it, and by the time the final break occurs, succeed in establishing a new current of the proper value of 50 amperes in the right direction. If this is accomplished when *e* leaves the brush, Fig. 331, then instead of having to break 90 amperes, the 50 amperes from *U* turns upward into *V*, joins in multiple with the 50 amperes from *W*, making 100 amperes, which comes down through the common lead to *f* and is picked up by the brush. The current thus finds a path to the brush without the necessity of arcing from the trailing edge of *e*. If the self-induction of the coil is high it may be that even a high resistance brush of usual width will not effect this result. If a broad brush which prolongs the duration of short circuit is used, it will sometimes effectually cure sparking that could not be cured in any other way. If, however, a broad high resistance brush, placed in the neutral position, still fails to prevent sparking, the brush position may be advanced in the direction of rotation until the coil *V* comes under the fringe of the flux from the pole which it is approaching. This causes *V* to cut lines of force in the opposite direction from that cut by coil *X*, which will generate an e.m.f. in the reverse direction. As the coil is on short circuit a very small e.m.f. will serve to rapidly choke down to a standstill the 40 amperes therein, and quickly build up the required current of 50 amperes in the opposite direction. This action, combined with the reversing tendency obtained by the broad high resistance brush, will effectually prevent sparking from self-induction.

When the field is undistorted the brushes may rest upon the line *A-B*, which is the no-load or theoretical neutral. When carrying a load the true neutral line perpendicular to the distorted field is *C-B*. To aid in the reversal of current in *V* it may be found necessary to advance the brushes slightly beyond this position to the line *D-B*. This is called the diameter of commutation.

Commutating Poles

Many modern generators and motors employ a separate field winding placed on a narrow pole situated in the gap space midway between the main field poles. The function of this winding is to resist armature reaction and consequent field distortion. It produces a magneto-motive-force diametrically opposed to that of the armature. It is connected in series with the arma-

ture and is at all times not only opposed to but proportional in magnitude to the armature's m.m.f. It not only opposes field distortion, but it also actually supplies a flux through the short-circuited coil expressly for commutating purposes. It therefore takes the place of the commutating fringe required from the pole tip *N*, Fig. 331. When such a commutating pole and winding are employed, higher voltages per coil and consequently between segments, are possible than without such winding. Furthermore, as the action of this winding automatically varies with the load, it exerts the proper counter-balancing effect against armature reaction at all loads. There is, then, but one neutral line for all loads, and the brushes are never shifted.

Prevention of Sparking

In the original design of a machine the following points should be observed to prevent inherent sparking:

First, the winding should be subdivided into many coils of few convolutions in order that commutation may be effected (that is, the reversal of current may be accomplished) in detail. The e.m.f. of self-induction varies as the square of the number of convolutions in a coil. Thus, if an armature consisted of 40 coils of 10 convolutions each or 400 convolutions and 800 conductors; and another armature consisted of 80 coils of 5 convolutions each or 400 convolutions and 800 conductors, the latter, while having the same total number of conductors and thus being able to deliver the same voltage, would have just one-fourth the tendency of the former to spark from self induction.

Second, unless the machine has commutating poles, the field magnets should be relatively powerful to avoid distortion. With a weak field no sparkless point can be found.

Third, if the machine is not provided with commutating poles, the pole faces should be so shaped as to give a fringe of magnetic field of sufficient intensity to commutate properly.

Fourth, the brushes should be of sufficient resistance and width to prolong the short circuit on the coil the required time.

Causes of Sparking in Operation

The following are the principal causes of sparking due to improper operation of machines:

First, brushes **not on the diameter of commutation.** The no-load neutral may be found in the following way. With the armature standing still, place a low reading voltmeter across the

brushes, Fig. 333. Energize the field to about one-half strength. Suddenly break the field circuit. If the brushes are not in the proper position a momentary kick will be observed on the voltmeter. Shift the brushes and repeat the operation on the field until no kick is observed. This is sometimes called the **kick neutral.** It is the proper position for the brushes at no-load. It will be observed that the voltage, if any, obtained on the voltmeter under these conditions is not due to the rotation of the armature but is due to the generation of unequal e.m.fs. in the sections which should exactly balance each other. When the voltmeter fails to respond, the brushes are exactly perpendicular to the field.

A better method of obtaining the **no-load neutral** is to operate the machine as a motor. Take the speed. Reverse the con-

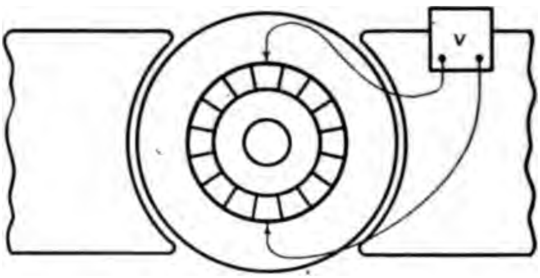


FIG. 333.

nections and run the machine in the opposite direction. Again take the speed. Shift the brushes until speed is the same in both directions.

To obtain the **full-load neutral,** place the brushes in what appears to be the sparkless position when the machine is carrying its load. Take leads extending from a low reading voltmeter and explore the commutator, touching the leads on adjacent segments and move them back and forth, Fig. 334. When the voltmeter reads zero it is bridging a coil which is cutting no lines of force and is therefore in the exact neutral position. The brushes should be shifted to this point. This position may be roughly approximated without the voltmeter by simply adjusting the rocker arm while the machine is carrying its load until all sparking disappears or at least reaches a minimum value.

Brushes not Equally Spaced.—With metallic brushes set upon the commutator at an angle and adjusted in their holders, one

may be advanced so that the distance between brushes of opposite polarity differs. This would divide the armature into unequal sections as far as potential is concerned and would cause sparking. The remedy is to adjust the brushes so that they are equally spaced.

Brushes not in alignment on the same brush holder stud: Where the amount of current to be collected requires several brushes in parallel, it may be that one will be advanced beyond the others if they are placed at an oblique angle to the commutator. The total brush span would then be too great and sparking would result from the larger number of coils short-circuited. The remedy would be to place the brushes all in line. If the

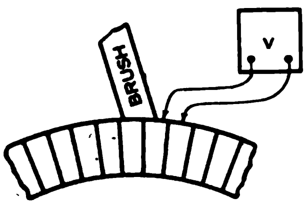


FIG. 334.

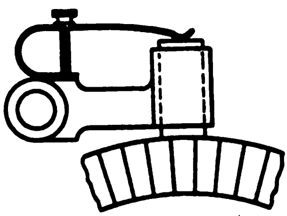


FIG. 335.

type of brush holder be that shown in Fig. 335, and the brushes are radial, there is little danger of lack of alignment.

If brushes are set with **too much** or **too little pressure** there will be sparking. Too much pressure scores the commutator and too little pressure admits of bouncing. Stationary machinery requires a brush pressure of from 1 to 4 pounds per square inch. Railway motors, which are subjected to severe vibration, require a tension of 4 to 7 pounds per square inch.

If brushes are set so as to **not** get a **perfect bevel** on the commutator there will be sparking due to insufficient area of contact. Carbon brushes are usually square on the end when manufactured. After being placed on the commutator under proper tension, a piece of sand paper should be slipped under the brush with the sanded surface against the brush. This strip of paper should then be drawn back and forth along the commutator until it grinds the end of the brush concave to fit the convexity of the commutator.

An **open wire** in the armature or a **loose connection** in the commutator will cause a hot, blue, crackling spark which burns

the commutator and brush. Suppose a break occurs in a winding at the point *L*, Fig. 331, in the wire leading to a segment. As the segment *d* passes under the brush it will collect current from the right side of the armature, but when *d* leaves the brush, current cannot flow through the coil, *L'*, because of the break at *L*. The entire current from this half of the armature must therefore arc from the point *K* to the brush. This burns and blackens the trailing edge of the segment. When the machine is shut down the break can readily be located because it is in the connections leading to the coil which bridges segments *e-d*, between which is the burned edge, *K*. A temporary remedy for the difficulty is to put a jumper across the commutator segments *e-d*. This may be a wire soldered to both segments, or, in a small motor, a drop of solder at *K* is sufficient to bridge the gap at *L*. This, however, is but a temporary expedient. As soon as possible the connections should be opened up, the actual break located by inspection, and a permanent repair made.

If a machine is carrying a **heavy overload,** there will be an abnormal distortion of the field and consequent sparking. Such a condition would be evident from an inspection of the ammeter, which shows the load carried. The remedy, of course, would be to lighten the load. Should it be impossible to disconnect any of the load, sparking might be reduced by lowering the speed of the generator slightly and cutting out resistance in the field rheostat to strengthen the field. Sometimes an adjustment of this sort can be made so as to strengthen the opposition to armature reaction although at reduced potential.

Sparking will occur from **moisture in the armature winding.** If the armature has been submerged in water or has been newly wound, with the insulation not thoroughly dried or baked, there may be internal short circuiting. Stray currents would cause heating of the windings and an unbalancing of the delivered potentials. Sparking from this cause would be accompanied by smoking of the insulation, and evidence of abnormal stresses within. A remedy would be to operate the armature on short circuit in a weak field. The field current should be adjusted so that the short-circuit current is the full load current for which the armature is designed. (This method gives a very low voltage between conductors while running on short circuit.)

If possible it would be preferable to thoroughly bake the armature in a hot room or box until all moisture is excluded. A simple oven for this purpose can be made by using a box slightly larger than the armature, lining it with asbestos, having holes in the top and bottom and a bank of incandescent lamps under the armature in the box. The heat generated by the lamps is sufficient to thoroughly dry out the armature.

A **high, low,** or **loose commutator bar** will cause the brushes to bounce and spark. The large number of metallic and insulating segments of which a commutator is composed make it very difficult to insure that all are securely locked in position. Should

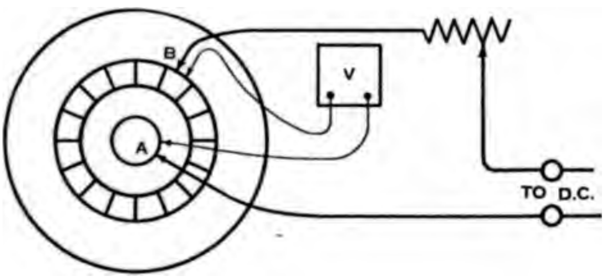


FIG. 336.

one get loose it will either rise or settle in place. Any irregularity in the surface will cause sparking. If the bar is too high it may be tapped into place gently with a mallet. Under any such circumstances the end clamp ring should be tightened up and the commutator turned down true. Older machines, and especially small ones, require that the armature be taken out and swung in a lathe to true it up. Now, however, a device is obtainable which goes on the machine itself and permits the turning down of the commutator in its own bearings without removing it from the frame. Under these conditions the brushes should be removed and the commutator should not be driven too fast.

If an armature **winding or commutator segment** is **grounded** there will be sparking at the brushes. One ground on the armature will not cause any trouble, but two grounds will permit the flow of a current between points of different potential through the winding and core. This unbalances the armature electrically and causes sparking. Usually a ring of fire is formed which encircles the entire commutator. One method of locating a

ground is shown in Fig. 336. Here a direct-current source of supply is led through a resistance to the armature to be tested. Lead *A* terminates on the shaft, while lead *B* is moved around the commutator, touching the segments one after the other. A low reading voltmeter, which is placed across the leads, will indicate the ground. The grounded coil is one of those connected to that segment which gives a minimum deflection on the voltmeter, or the segment itself may be grounded.

Another method is illustrated in Fig. 337. Here a source of supply, which may be a storage battery of three cells, is connected to the commutator and shaft through a suitable resistance, *R*, and ammeter, *A*. The lead, *B*, is moved around the commutator. *R* must be kept constant. One of the coils

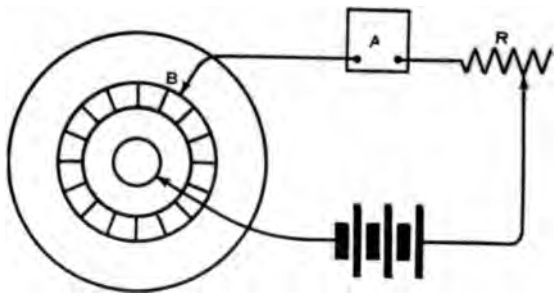


Fig. 337.

connecting to the segment which indicates the highest current value is grounded, and the segment itself may be grounded.

By employing one of these methods, only the coils connected to a single segment need be disconnected. These methods are used to a considerable extent in connection with railway and other types of armatures.

Should these methods fail, it may be necessary to entirely disconnect the leads between the commutator and the coils and apply a test to determine whether the winding or the segments are grounded. Individual segments and coils may be then tested to locate the ground.

A **rough** or **ridged commutator** causes sparking. It should therefore be kept true and perfectly smooth. Commutators should not be sand papered or kept bright. With proper attention and reasonable care, they will soon acquire a dark glazed

surface which is very durable. Railway motor commutators especially last longer if the insulating mica between the copper segments is recessed. Circular saws are employed to cut the mica about $\frac{1}{32}$ of an inch below the surface of the copper. Commutators so treated wear very much longer than those where the mica and copper are flush. This is because of the tendency for copper to wear away faster than mica. The mica protrudes and raises the brushes, interrupting the circuit and causing sparking, which burns away the copper.

Metallic brushes are used on commutators where large currents must be collected from a small surface. Laminated copper wire gauze brushes will collect from 100 to 150 amperes per square inch of contact surface. For collecting large currents, these brushes have been largely replaced by a composition consisting of approximately 75% carbon dust and 25% copper dust, which are moulded under hydraulic pressure, after being mixed with a binder. "Morganite" brushes are of this type. The majority of direct-current machines employ a carbon brush which has more or less graphite mixed with it. Some of these brushes contain as much as 50% graphite. No lubricant is required for a carbon-graphite brush. Carbon brushes will carry approximately 30 amperes per square inch of contact surface. It is not advisable to lubricate commutators. The most that should ever be done is to apply a small amount of vaseline or clean light machine oil to the commutator while the machine is running. After distributing it over the surface, the commutator should be wiped with a piece of woolen felt. (Cotton waste should never be used.)

A short circuit in a coil or between adjacent commutator segments will cause sparking at the brushes. Thus, suppose that segments *f* and *g* of Fig. 331 become short-circuited by a piece of foreign conducting material such as solder getting between them. The coil *W* would be placed on short circuit through a very low resistance. In the position shown, where it is generating practically no voltage, no harm would result, but when it moves down into the field to the position *T*, the voltage generated in it would produce an abnormally large current on short circuit. This would overheat the coil. As this coil is practically short-circuited, and therefore delivers no e.m.f. in the armature circuit, that section of the armature in which it is connected

lacks that much voltage. The result is that the winding is unbalanced and sparking ensues. Such a short-circuited coil can readily be located by inspection when the machine is stopped. By running the hand over the armature winding, one may detect an excessively hot coil. Often the insulation is smoking. The remedy, of course, is to examine the segments f and g and the connections leading therefrom, until the short circuit is located and opened.

A common cause of sparking is the **embedding of carbon** or **copper dust** in the mica between the segments. These cause a partial short circuit and feeble streaks or rings of fire encircle the commutator. If the sparking becomes pronounced, the application of a little very fine sand paper will often cut off the mica with the embedded particles which cause the sparking. If the commutator is undercut, it should be stopped and the accumulated dust scraped from between the segments with a suitable tool.

A commutator sometimes exhibits a tendency to develop a **flat spot** on one part of the segment. Like a flat on a car wheel, this trouble, once started, rapidly increases in magnitude. It is generally believed that this is due either to loose bearings, unbalancing of the armature mechanically, or some other contributing cause which brings about eccentricity in the rotation. The armature and commutator thus develop a throw at one point in the revolution which causes the brush to bounce and eventually pound a segment flat. The remedy, of course, is to see that the bearings are as tight as practical. The commutator should be turned down if necessary.

If an armature of a multipolar machine is parallel wound and not provided with any cross-connecting equalizing rings, it will become electrically unbalanced if the bearings wear so that the armature settles. This will cause unequal voltages in the various sections and sparking due to bucking will ensue.

Sometimes a **loose** or **corroded connection** in one of the several possible places **in the field circuit** will cause a weak field, or if the field circuit is broken intermittently, the armature reaction will distort the flux and cause intermittent sparking. The remedy is to see that all field connections are kept tight.

If a machine is driven at too **high a speed** there will be **abnormal vibration** and consequent sparking. At high speed it will also

be necessary to reduce the field current to hold the voltage at the proper value. The armature could thus more readily distort the weakened field and sparking would ensue. Under such conditions it would be wise to reduce the speed of the generator, and, if necessary, provide it with a larger pulley if the machine is a belted one. The field current could then be increased by cutting out resistance from the rheostat. The stronger field would resist armature reaction and would be less distorted. Sparking would thus be prevented.

SECTION VIII CHAPTER VII

DIRECT-CURRENT GENERATORS

CAUSES OF SPARKING AND REMEDIES

1. Clearly explain by the aid of a sketch, the process of commutation in a generator.
2. Why does self-induction in an armature coil cause sparking at the brush?
3. What effect has the number of convolutions in a coil upon the sparking due to self-induction?
4. What are the relative advantages of low resistance brushes and high resistance brushes with regard to sparking?
5. What are the relative advantages of narrow brushes and broad brushes with reference to sparking?
6. What is the result of advancing the brushes slightly beyond the true neutral line?
7. What precautions should be observed in the original design of a generator in order to avoid inherent sparking?
8. Distinguish between the theoretical neutral line, the true neutral line and the diameter of commutation. Where should the brushes be placed? Explain fully.
9. When the load varies, must the brush position be changed?
10. The armatures of two generators of the same size have the same number of conductors. One has 60 coils of 10 convolutions each and the other has 120 coils of 5 convolutions each. What are the relative advantages of these two arrangements?
11. Explain the object of commutating poles. How are their windings connected? Where should the brushes be placed on a machine with such poles? Should the brushes be shifted under changes in load?
12. How will sparking be caused by brushes not of the diameter of commutation?
13. How is the location of the "no load neutral line" obtained?
14. How is the location of the "full load neutral line" obtained?
15. Why will unequal spacing between brushes of opposite polarity cause sparking?

16. (*a*) What is a suitable brush tension on stationary machines?
    (*b*) What should it be on railway motors?
    (*c*) What is the effect of too much or too little brush tension?

17. Why is sparking caused by brushes set so as not to give the full bevel on the commutator? How should brushes be trimmed?

18. Why does an open wire or loose connection in the armature or commutator cause sparking? How can the open be located? How can it be remedied temporarily?

19. Why does a heavy overload cause sparking?

20. How does moisture in an armature bring about sparking?

21. Why does a high or low commutator bar cause sparking? How should it be remedied?

22. If the winding or a commutator segment is grounded what will be the nature of the spark produced? What causes this spark? Will one ground cause trouble?

23. How will one of the grounded points be located by means of a voltmeter? Sketch.

24. How will the grounded point in an armature be located with an ammeter? Sketch.

25. How will a short-circuited coil cause sparking and how may such a short-circuit be located?

26. If a fine ring of fire occasionally encircles the commutator, what is the probable cause? How may it be remedied?

27. If a generator is operated at too high a speed, how will this result in sparking? Will a reduction in speed remedy the difficulty? Why?

DIRECT-CURRENT GENERATORS

SERIES AND SHUNT GENERATORS

Self-exciting generators may have their field windings connected in series with the armature, Fig. 338, or in shunt with the armature, Fig. 339.

Series Generators.—Early generators for arc lighting were series connected and were termed constant current machines. They were particularly adapted for furnishing approximately a constant current and a variable potential. The external circuit was series connected like the internal. It usually consisted of arc lamps, all looped in series upon one line. The resistance of the generator's field was relatively low and the entire current

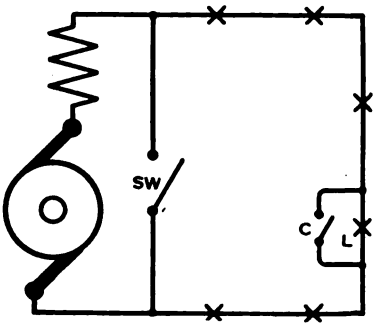


FIG. 338.—Series connected generator.

from the armature passed through it on its way to the line. To put such a machine in operation, the switch, *Sw*, Fig. 338, was closed, which short-circuited the armature and field in series. All self-exciting machines depend upon residual magnetism to start their operation. In the ordinary process of machining the frame, some magnetism is developed. The machine depends upon this for building up its field. In the absence of any residual field, some magnetism must be developed by excitation from an outside source. This can readily be supplied either from a few cells of battery or from another generator. Assume a residual field to begin with, the switch, *Sw*, closed, and the armature driven at its normal speed by a prime-mover. The armature

conductors cut the few lines of force due to residual magnetism and generate a minute e.m.f. This produces a small current in the path of low resistance offered by the armature and field. This current is able to establish a few more lines of force. The armature being driven at a constant speed now cuts this increased flux and produces more voltage and the increased voltage produces more current. The increased current develops more flux. Thus, voltage, current and flux continue to build up. The current might eventually rise until it destroyed the machine were it not for the saturation of the field. As the saturation point approaches an increase in current does not succeed in producing any material increase in flux. As the flux does not rise the voltage cannot rise. Thus any further building up is avoided.

Armature reaction also increases with the current. This prevents the field flux from crossing the armature and thus aids in holding down the generated voltage. This machine depends for its regulation upon an exaggerated armature reaction. The armature winding is made with a relatively high magneto-motive-force. It is thus capable of producing wide changes in field flux across it by its varying reaction.

After the machine has built up, *Sw* may be opened, provided there is an external circuit through which the current can be diverted. The current is thus transferred from the short circuit to the external load. Assume a load of a certain number of lamps in series, and the machine delivering a constant current of 10 amperes with the switch, *Sw*, open. To turn out a lamp it is necessary to place a short circuit around it as at *C*. This reduces the external resistance. The natural effect would be an increase in current, which, passing through the series field, would produce more voltage and still more current. That is what would happen with an unsaturated field with an armature of small reaction. What actually happens is this: the slight increase in current accompanying the short circuiting of the lamp brings about a considerable increase in armature reaction. This opposes and reduces the field flux, which crosses the armature and actually brings about a reduction in voltage, preventing any further increase in current. If the switch, *C*, is opened, the first effect will be to slightly reduce the current, due to the insertion of the lamp, *L*. The armature reaction now decreases sufficiently to allow the field to establish more flux across it. This causes a

rise in voltage sufficient to care for the added resistance of the lamp *L* without an appreciable reduction in current. Thus, while the resistance of the external circuit may vary widely, the voltage varies almost as widely due to the reaction of the armature on the field flux and the resulting current changes very little.

It does no harm to short-circuit a series dynamo because the armature reaction maintains the current at normal value. It might burn out such a machine, however, to open the circuit upon it. Thus, if the external line should open, the collapse of the flux on the field winding would generate an enormous e.m.f. of self-induction. This could very easily puncture the insulation on either armature or field. To guard against such a contingency, this type of machine is provided with an automatic short-circuiting device which operates in the event of opening the main line.

Series circuits are commonly used for both incandescent and arc lighting. Series generators, however, are not employed to operate them because of their inefficiency. Such circuits are usually supplied today from large alternators through special devices arranged to maintain a constant current in the line.

Shunt Generators

Shunt connected generators are well adapted for maintaining a constant potential with a variable current output. In Fig. 339 the switches, *Sw*, are opened at the start in order that the armature and field may form a closed circuit by themselves, as in Fig. 338. This machine builds up upon a residual field on the same principle as the series machine. Saturation of the field prevents an indefinite rise of current and voltage. In this machine the armature has a relatively low resistance while the field consists of many convolutions of fine wire and consequently has a high resistance. When the voltage is fully established, switches *Sw* may be closed, connecting the external load. This consists of lamps in multiple, so the external circuit, like the internal, is shunt connected.

The principle upon which this machine regulates is as follows: The field forms a branch, or independent circuit, separate from the load, *L*. As the armature is driven at a constant speed it will generate a constant voltage provided the field strength is

constant. Assuming for the moment a constant voltage from the armature, it is evident that it will deliver a constant current in the shunt field winding, because of its fixed resistance. If this current is constant, then the flux across the armature produced by that current will also be constant. The flux being constant, the delivered voltage will be constant. Next, consider the effect of altering the load upon the machine. Should additional lamps be turned on, in multiple, the external resistance falls. If the armature resistance were high, the additional current would cause considerable drop in potential in the armature and therefore at the brushes. By making the armature of exceedingly low resistance, however, the added current does not

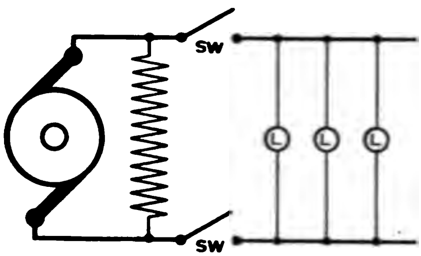


FIG. 339.—Shunt connected generator.

produce an appreciable increased drop, and the brush voltage is practically the same as before the additional load was turned on. The current furnished from the brushes to the shunt field will not appreciably alter. If this does not alter, the flux produced by it will be the same, and the generated voltage will not change. As a matter of fact, the voltage of these generators does alter slightly, just as the current altered slightly in the series machine, but by making the armature resistance very low, any increase in load produces but a small variation in brush voltage. Disconnecting some of the lamps produces the reverse effect. If the current in the armature decreases, the brush potential rises slightly, which correspondingly effects the shunt field, bringing about a slight increase in potential. In general, however, the shunt machine furnishes an approximately constant potential while the current varies widely with the load, just as a series machine furnished an approximately constant current while the potential varied widely with the load.

Armature reaction in the shunt machine is intentionally made

very low so as not to perceptibly disturb the field and the resulting flux. Armature reaction in the series machine was intentionally made very high so that it might materially disturb the field and the resulting flux.

No harm results from opening the external circuit on a shunt machine. **Under no circumstances, however, should a shunt machine be short-circuited.** To do so would, in all probability, burn out the armature winding. It might be expected that to short-circuit such a machine would deprive the shunt field of its current and consequent flux. Therefore the armature would be unable to furnish a dangerously high current. However, the

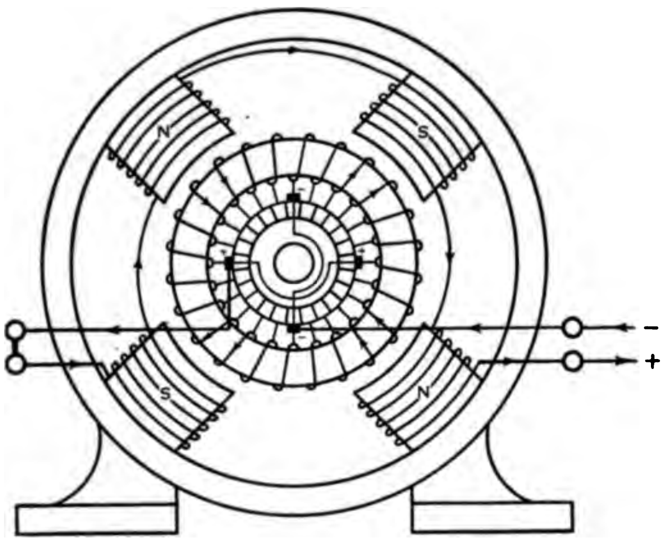


FIG. 340.—Series generator.

self-induction of the shunt field and the hysteresis of the frame tend to prolong the field magnetism for a considerable interval after a short circuit is effected. The current passing through the short circuit may then be sufficiently large to burn out the armature winding before the field dies.

Open circuiting a **series** machine is accompanied by the generation of an **excessive voltage. Short-circuiting** a **shunt** machine is accompanied by the production of an **excessive current.** Fig. 340 shows the connections of the field and armature

in a multipolar ring series machine. Fig. 341 shows the connections of a shunt connected multipolar machine with a ring armature.

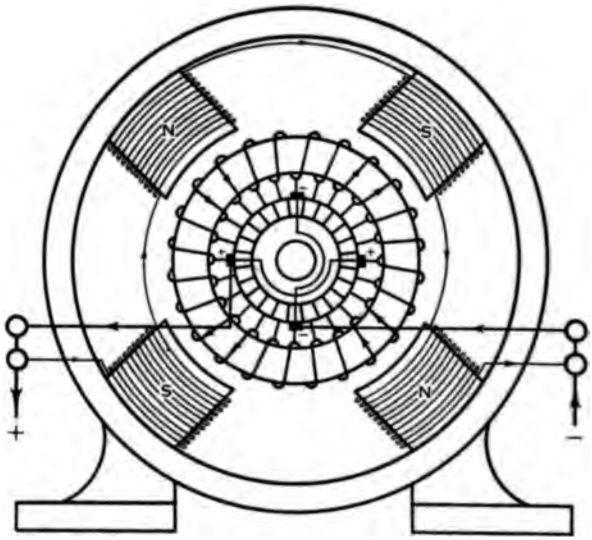


Fig. 341.—Shunt generator.

SECTION VIII CHAPTER VIII

DIRECT CURRENT GENERATORS

SERIES AND SHUNT GENERATORS

1. Sketch a series generator connected to a suitable external circuit.
2. Explain the method of starting up a series generator. What precautions should be observed? When and how should the load be thrown on?
3. What current density should be allowed per square inch for copper and for carbon brushes?
4. What kind of current and potential is a series generator adapted to furnish? How does it regulate to produce this result under variations in load?
5. Is it safe to open-circuit or short-circuit a series generator? What results, if any, are apt to follow either of these operations?
6. Is armature reaction great or small in a series machine? Is the field relatively feeble or strong?
7. What are the relative resistances of the armature and field windings of a series generator?
8. Sketch a shunt generator suitably connected to a an external circuit.
9. Explain the method of starting up a shunt generator. What precautions should be observed? When and how should the load be thrown on?
10. What kind of current and potential is a shunt generator adapted to furnish? How does it regulate to produce this result under variations in load?
11. Is it safe to open-circuit or short-circuit a shunt generator? What results, if any, are apt to follow either of these operations?
12. What is the relative armature reaction in a shunt generator? What is the relative field strength?
13. What are the relative resistances of the armature and field windings of a shunt generator?

SECTION VIII CHAPTER IX

DIRECT-CURRENT GENERATORS

REGULATORS FOR SERIES AND SHUNT GENERATORS

Series generators have an inherent tendency to maintain a constant current and shunt generators have an inherent tendency to maintain a constant potential under changes in load. In order that these machines might regulate more closely, automatic regulators have been devised.

All regulators employ resistance units which are cut in and out of circuit to adjust the voltage or current as may be necessary.

Resistance is an inherent property of a substance, opposed to the passage of current therein. A **resistor** is a resistance unit, connected in a circuit for the purpose of introducing resistance. A **rheostat** is a combination of resistors with a device whereby the effective resistance of the circuit can be varied.

The most widely used material in rheostats is iron, either in the form of a wire or cast grids. Heat causes the iron to rust, hence it should be protected. The wire is usually coated with tin, while cast iron grids are painted with aluminum paint. Iron possesses a resistance of from 7 to 11 times the resistance of copper and is cheap and durable. A table giving the carrying capacity of tinned iron wire of various sizes appears on the following page.

A variety of alloys have been designed, which have high specific resistances. The most widely known of these is German silver. This consists of a mixture of copper, nickel and zinc in various proportions. 18% nickel gives 18 times the resistance of copper at 25 degrees Centigrade. 30% nickel gives 28 times the resistance of copper at 25 degrees Centigrade. "Advance" is a copper-nickel alloy containing no zinc, having a very low temperature coefficient and a resistance of 28 times that of copper. "Climax" is a nickel-steel alloy having 50 times the resistance of copper. It also possesses a low temperature coefficient and is a cheap material to use when resistance is the only consideration.

"Nichrome" is a practically non-corrosive alloy having an extremely high melting point. It does not melt under 2,800 degrees Fahrenheit and will work at temperatures over one thousand degrees. It possesses 60 times the resistance of copper and is widely used in electrical heating devices.

Tinned Iron Wire

Size of wire B. & S.	Safe current in wood frame.	Safe current in iron frame.	Safe current for one minute.	Feet per ohm.
8	17.4	20.3	43.6	250
9	14.6	17.1	36.6	173
10	12.3	14.3	30.8	137
11	10.3	12.0	25.8	108
12	8.7	10.1	21.7	86.4
13	7.3	8.5	18.3	68.5
14	6.1	7.1	15.3	54.3
15	5.1	6.0	12.9	43.1
16	4.3	5.0	10.8	34.1
17	3.6	4.2	9.1	27.1
18	3.00	3.5	7.6	24.3
19	2.52	2.9	6.3	16.5
20	2.17	2.5	5.4	13.5
21	1.82	2.1	4.5	10.7
22	1.53	1.77	3.8	8.49
23	1.28	1.49	3.2	6.73
24	1.08	1.20	2.3	5.34

Rheostats may be constructed of carbon, either in the form of rods or discs. This material has a resistance of more than two thousand times that of copper. It is frequently used in the form of stacks of discs about the size of a silver dollar. Such a stack forms a resistance which varies widely under pressure. Carbon itself does not change in resistance under pressure. Stacks of carbon discs or plates do change in resistance because the pressure varies the resistance of the contact surface between adjacent discs.

Water may be used as the conducting medium in a rheostat. Any vessel, preferably a jar, a tank or barrel, may be employed.

An electrode should be placed in the bottom, connecting to the external circuit through an insulating wire. Another electrode is lowered into the water as shown in Fig. 342. The water may be made conducting by the addition of common salt in varying quantities. Such a rheostat is easily assembled and very flexible. It may be used to handle currents of any value by varying the dimensions. It should never be used as a permanent affair because of its instability. The adjustable electrodes must be constantly changed in position to hold the current constant, as the resistance of the solution alters with every change in temperature.

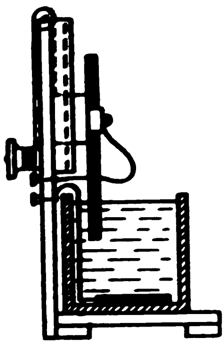


Fig. 342. — Water rheostat.

Brush Regulator

Fig. 343 represents the principle of the Brush regulator for maintaining a constant current on a series arc light circuit. The current (usually about 9 amperes) passes from the armature G, thence through the series field F, and to a wall magnet, W-M, on its way to the external circuit, consisting of arc lamps in series. Should it be desired to cut out some of the lamps at L, the switch S is closed. The tendency is for the current to rise. The solenoidal wall magnet attracts its core and raises a lever, bring-

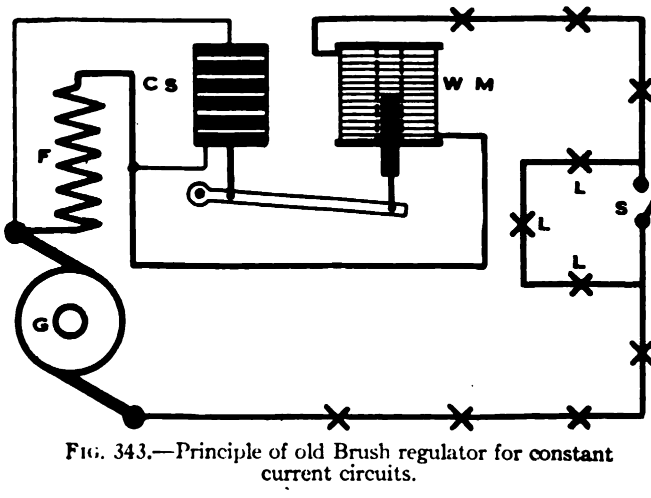


Fig. 343.—Principle of old Brush regulator for constant current circuits.

ing increased pressure to bear upon a stack of carbon discs, *C-S*, which shunts the generator field. This lowers the resistance of the by-path and diverts some of the current from the field around through the carbon stack. This weakens the field and lowers the voltage in proportion to the number of lamps cut out, and thereby checks the attempted rise in current. After switch *S* is opened the reverse action takes place. The first effect is for the current to fall. This weakens the pull of the solenoid and reduces the pressure on the carbon stack. Its resistance rises and compels some of the current which went around the field to now take the path through the field. The voltage therefore rises sufficiently to maintain the current in the lamps *L-L* at nearly the same value as before.

Thomson-Houston Regulator

Another regulator working on an entirely different principle is shown in Fig. 344. This was designed by the Thomson-Houston Company for controlling the current output in their machine. Suppose there is a difference of potential of 100 volts between two brushes in a bipolar field as in Fig. 345. If, now,

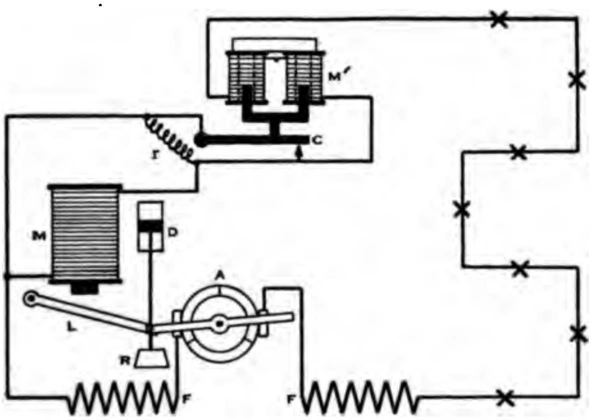


FIG. 344.—Principle of old Thomson-Houston regulator for constant current circuits.

the brush *C* is moved down around the commutator 90 degrees and the brush *D* is moved in the opposite direction up around the commutator 90 degrees, it will be evident that the potential of *C* will fall 50 volts and the potential of *D* will be raised 50 volts. Thus, in the position shown, Fig. 346, they will be at the same potential, which means that there is no difference of potential

between them. If then the rocker arm of a machine is shifted 90 degrees, the voltage will be varied from maximum to zero. On a closed coil machine this would result in sparking. The earliest arc lighting generators employed open coil armatures and sparked inherently at the brushes. There would be no increased sparking if brush shifting were resorted to as a method of control. The Thomson-Houston generator employed this principle. In Fig. 344 a rocker arm, to which the brushes were attached, was rotated by means of a lever, *L*, attached to the armature of an electro-magnet *M*, mounted on the frame of the machine. A scissors-like arrangement, not shown in the sketch, was also employed at the same time to vary the span of the brushes of one polarity. The rocker arm was weighted at *R* so that it rotated

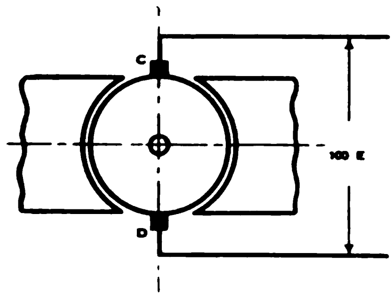


Fig. 345.

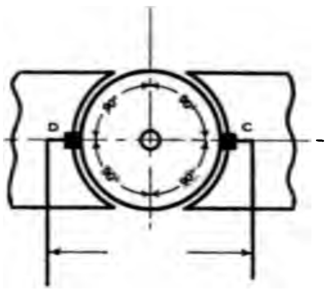


Fig. 346.

the brushes to the point of maximum potential, raising the current. The current passed from the armature *A* through the field coils *F*, thence via the contact *C* and wall magnet *M'* to arc lamps in the external circuit, and back to the machine. As the current rose, the magnet *M'* increased in strength until finally it reached a maximum and broke the contact at *C*. A high resistant shunt, *r*, prevented sparking at this contact. The current which originally passed through *C* was then diverted through *M*, which immediately operated to lift the lever *L* and rotate the rocker arm to a point of lower potential. A sudden movement of the rocker arm in either direction was prevented by the dash pot shown at *D*. As the potential and current fell, *M'* weakened. At the particular value for which this magnet was adjusted, its armature dropped and the contact *C* closed. This short-circuited *M*, which released *L*. The counter-weight immediately commenced to rotate the rocker arm toward a higher potential point and the current commenced to rise.

This cycle of operation was rapid, the regulator constantly varying the current within quite narrow limits. If lamps were turned on or off, the regulator held the current at a steady value. A later Brush General Electric arc light generator embodied both principles above explained, that is, it shifted the brushes and shunted the field.

Hand Control

The first method of adjusting the potential of a shunt dynamo was the hand regulator invented by Edison, Fig. 347. This consisted of a rheostat *R*, inserted in series with the field *F*. When the load increased externally, it became necessary to adjust

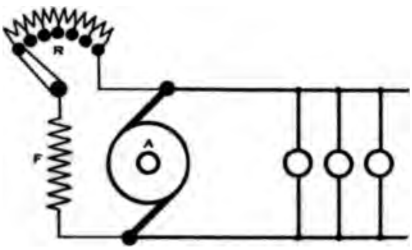


FIG. 347.—Edison field regulator.

the voltage. The rheostat arm was then moved by hand, cutting out resistance, which would raise the field strength and correct the voltage

Chapman Regulator

Automatic regulators have been designed which take care of load changes with little or no adjustment of the hand regulator. One of the earliest types was the Chapman voltage regulator shown in Fig. 348. Here the field rheostat, *R*, in series with the shunt field, *F*, instead of being operated by hand, was worked by two solenoidal magnets, *M* and *M'*, which were attached to opposite ends of a lever *A*, which in turn moved the rheostat arm *S*. These electro-magnets were cut in and out of the circuit by means of a voltmeter relay, *VR*, which was connected across the line in series with a resistance ballast, consisting of an incandescent lamp, *L*. Within the coil of this relay was a soft iron pivoted disc, which tended to place itself on edge vertically under the action of the coil against which an adjustable coiled spring, *C*, tended to place it horizontally. Extending perpendicularly from this disc was a platinum tipped tongue, which moved

between two adjustable contacts, D and D'. If the external load increased, the voltage would fall. This would lower the pressure on the voltmeter relay. The spring C would pull the disc toward the horizontal and the platinum tongue would touch the contact D. This would close the circuit on the magnet M, which would pull down the lever A and carry the rheostat arm S to the right, thus cutting out resistance from the field circuit and raising the voltage. A dash pot was attached to this magnet so as to prevent too sudden a movement. When the voltage had been raised to normal value, the disc in the voltmeter relay would move toward the perpendicular and the contact at D would be broken. If the load were decreased, the voltage

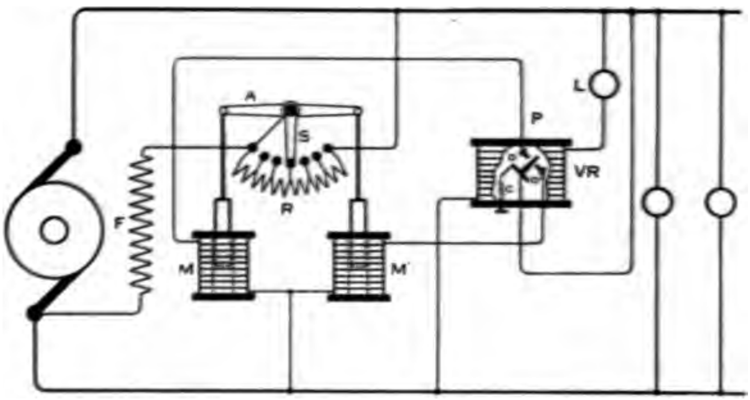


Fig. 348.—Chapman voltage regulator for constant potential circuits.

of the machine would rise. This would raise the strength of the voltmeter relay. The disc would move further toward the perpendicular and close the contact at D'. This would complete the circuit through magnet M', which would reverse the movement of the rheostat arm, inserting more resistance in the field circuit and lowering the voltage. To prevent sparking at the contacts, D and D', each of the operating magnets, M and M', was provided with two distinct windings, wound side by side, convolution for convolution and layer for layer One of these windings energized the core. The other winding, entirely insulated from the first, was short-circuited upon itself. When the contact at D or D' was broken, a voltage was induced by mutual induction from the operating winding to the idle winding. The resulting current served to sustain the flux in the core for an

appreciable time and thus very effectually prevented any sparking due to self-induction at either D or D'.

The objection to this type of the regulator is twofold. First, it is sluggish in its operation, and second, there is a tendency to "hunt." It is necessary that the voltage should actually change before the regulator will operate. Then, when the regulator tries to correct it, it is apt to overdo it, raising or lowering the potential beyond the required amount, oscillating in its operation until the desired voltage is attained.

Tirrill Regulator

A superior regulator designed by A. A. Tirrill is shown in Fig. 349. This is based upon the principle that by rapidly changing the voltage within very narrow limits, it may be main-

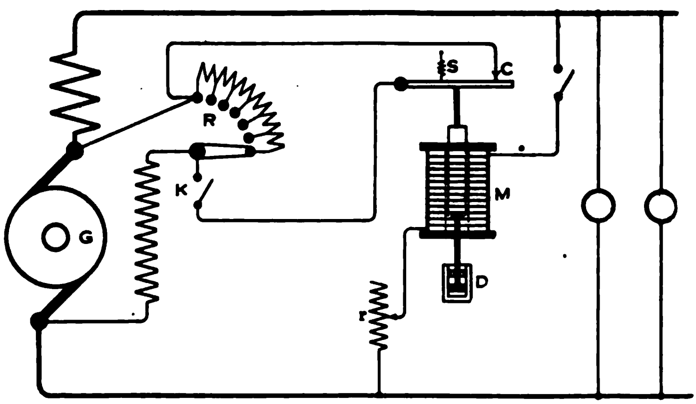


FIG. 349.—Simple form of Tirrill regulator.

tained very steady at the lamps. To effect this rapid fluctuation a voltmeter magnet M, connected in shunt with the line, is employed to rapidly short-circuit the terminals of the field rheostat, R, and as rapidly remove the short circuit. At the start, resistance is inserted in R until the machine's voltage is about 40% below normal. A switch at K is then closed. This completes the circuit through the contacts C, which are held together by the spring S, and the machine commences to build up its voltage. At the particular voltage for which the device is set by the adjustment of the resistance unit, r, say 110, the magnet pulls down its core and breaks the contact at C. This re-introduces the field rheostat R. As this was previously set

for 40% below normal potential, the voltage commences to fall. So sensitive is the apparatus, however, that it does not drop more than one volt, say, to 109, before the pull of the magnet on its core allows the spring S to close the contacts C and again short-circuit the rheostat R. The voltage immediately commences to build up but at 110 the contact at C is again broken and the cycle is repeated. A dash pot at D, containing water with a film of oil over it to prevent evaporation, steadies the movement of the core. The cycle of vibration is very rapid and the voltage varies within narrow limits. It matters not whether the load is increased or diminished, this regulator operates to maintain **not a constant,** but a **steady voltage** at all times.

Another Form of Tirrill Regulator

The regulator illustrated in Fig. 349 is adapted for small machines only. The contacts at C could not handle much current without serious sparking.

Fig. 350 represents the elementary circuits of a type TD (Tirrill Direct Current Regulator), for machines of moderate

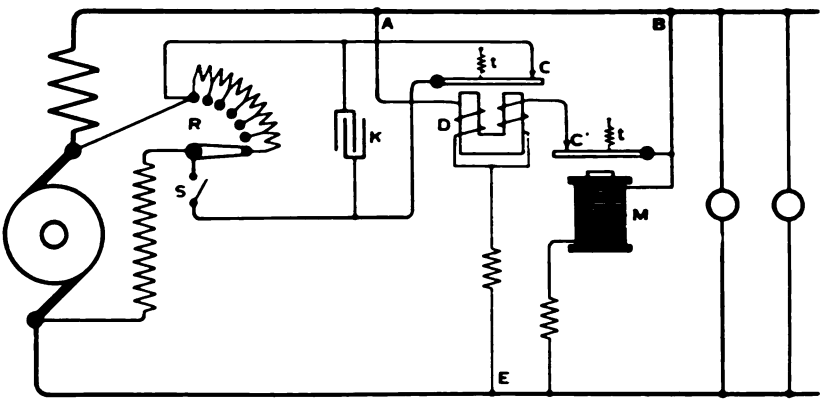


FIG. 350.—Scheme of connections for type "TD" Tirrill regulator built by the General Electric Co.

capacity. Here the work of short-circuiting and opening of the short circuit on the field rheostat R is removed from the main control magnet M, and a special differentially wound relay D is provided for this purpose.

With switch S open, the field rheostat R is set for 40% below normal voltage, and switch S is then closed. As the main control magnet M is adjusted to operate at a definite voltage,

say 110, if the voltage is now only 75, it will not attract its armature and spring *t* will keep the contact *C′* closed. This permits current to flow through the two windings of the differentially wound relay *D* from the points *A-B* to the point *E*. As there are two currents flowing in opposite directions through the two windings of equal length, which parallel each other throughout, the magnetic result is nil. The armature is not attracted and the spring *t* keeps the contact *C* closed. This places a short circuit upon the field rheostat *R* and the voltage begins to rise. At the particular value for which the magnet *M* is adjusted, say 110 volts, the armature is attracted and the contact *C′* is broken. This cuts out one winding, *B-E*, of the differential relay, leaving the other winding, *A-E*, in circuit. The relay is then operative, the armature is attracted and the contact *C* opens. This takes the short circuit off *R*. A rise in potential at the point *C* due to self-induction, which would tend to produce a spark at these contacts, is prevented by the condenser *K*, which is placed in shunt therewith and absorbs the energy of self-induction, thus

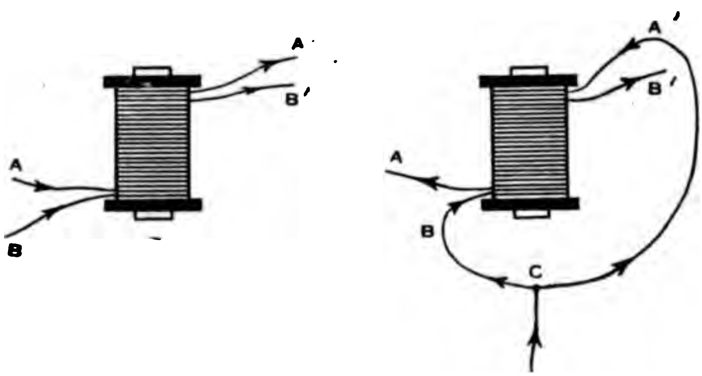


FIG. 351.

checking any serious rise in potential. The instant the contact at *C* opens, the resistance of *R* is reinserted in the field circuit and the voltage commences to fall. At about 109 volts or with a drop of not more than one volt, the magnet *M* releases its armature and the spring *t* closes contact *C′*. Relay *D* is now made differential and releases its armature and spring *t* closes contact *C*. The voltage commences to rise as before. The cycle of operation is rapid and is repeated continuously.

An understanding of the differential magnet D may be had from a study of Fig. 351. Suppose a coil to be wound with two wires A-A', B-B', which parallel each other convolution for convolution, layer for layer. It is evident that a current flowing through either of these windings would magnetize the core. Next suppose that the last end, A', is connected to the first end B and that a current admitted at the loop C flows in opposite directions through B-B' and A'-A. If these currents are equal it is evident that no magnetic effect will be produced. If, however, the circuit through the winding B-B' is interrupted, while that through A'-A is maintained, the magnet will operate. This is what happens to D, Fig. 350, when C' is opened and closed.

In order that the magnet M may be very sensitive, the armature must move through a very small range, the air gap being comparatively great. If, in Fig. 352, the magnet attracted its armature with a rise in potential of, say, one volt, and the arma-

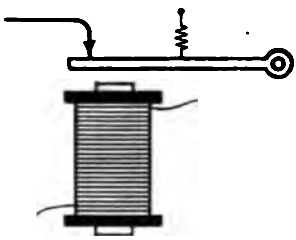


FIG. 352.

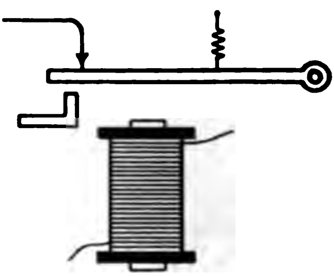


FIG. 353.

ture moved down in contact with the pole, the closing of the air gap would reduce the reluctance and increase the flux to such an extent that the voltage would probably have to be lowered 50% before the magnet would release its armature. If, on the other hand, the armature is situated a relatively great distance away from the magnet pole, as in Fig. 353, then if it moved downward upon a rise in potential of one volt, the reluctance of the magnetic circuit would not be appreciably decreased; the flux would then not rise, except in direct proportion to the increase in voltage. Now if the voltage is lowered one volt, the armature will be released and the upper contact will again be closed. This movement in both directions can only be effected when the air

gap is relatively great and the play of the armature relatively small. Obviously this limited travel of the armature would not be sufficient to break the circuit at C', Fig. 350, if these contacts carried any considerable current or if there was much e.m.f. of self-induction present. Hence the necessity for interposing the differential relay D, Fig. 350. As this relay is switched in and out of the circuit by the action of M, there is no restriction upon the play of its armature or the length of its air gap. Hence the contact C can be made massive and can open quickly and widely.

SECTION VIII CHAPTER IX

DIRECT-CURRENT GENERATORS

REGULATORS FOR SERIES AND SHUNT GENERATORS

1. What various materials are used in rheostats? What are the relative advantages of the different materials?
2. What is the composition of German silver? What is its resistance compared with copper?
3. What are the advantages and disadvantages of a water rheostat?
4. Explain the Brush regulator for maintaining a constant current on a series generator. Sketch.
5. Explain the Thompson-Houston regulator for maintaining a constant current on a series generator. Sketch.
6. Explain the Edison field regulator for maintaining a constant potential on a shunt generator. Sketch.
7. Explain the Chapman voltage regulator for maintaining a constant potential on a shunt generator. Sketch.
8. Explain the simplest form of Tirrill regulator for maintaining a constant potential on a shunt generator. Sketch.
9. Explain the "type TD" Tirrill regulator for maintaining a constant potential upon a shunt generator of suitable size. Sketch

DIRECT-CURRENT GENERATORS

COMPOUND WOUND GENERATORS; MULTIPOLAR MACHINES

The e.m.f. of a shunt machine falls under load from three causes.

First, the **ohmic drop** in the armature.

Second, armature reaction on the field flux.

Third, a consequent **fall in e.m.f.** and **current delivered to the field windings** due to causes one and two. Assume a shunt machine, Fig. 354, generating 100 volts with no load. This voltage will be delivered at the brushes. If the armature has a resistance of 0.1 ohms and a load of 10 amperes be connected, this current on its way to the load, flowing through the resistance of the

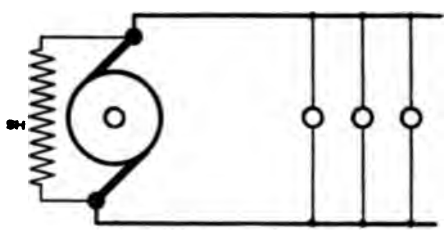


FIG. 354.

armature winding, would fall in potential $RI = E = 0.1 \times 10 = 1$ volt. Out of the 100 volts generated there would then be available only 99 at the brushes. Should a load of 20 amperes be connected, this current, flowing through the armature's resistance, would involve a drop of $0.1 \times 20 = 2$ volts. Out of the 100 volts generated, only 98 would now appear at the brushes. Thus the brush potential would fall with every increase in load.

Ten amperes in the armature would react upon the field flux and diminish to some extent the actual flux crossing the armature winding. This would reduce the actual voltage generated to something less than 100. If 20 amperes passed through the armature the reaction would be still greater and the actual voltage generated still further reduced. The combination of these

two losses lowers the actual voltage impressed on the shunt field, *Sh*, Fig. 354, so that it gets less current when the machine is carrying a load than when unloaded. There is thus less flux actually produced and the generated voltage is further lowered.

Next assume a machine with a series winding connected to an external circuit, *A*, Fig. 355. This should be a machine with an unsaturated field and small armature reaction. It is **not** an arc light machine where armature reaction was purposely exaggerated and where the field was highly saturated. Under the conditions assumed, if the external resistance of this machine is lowered by the addition of a load at *B*, the natural result will be to

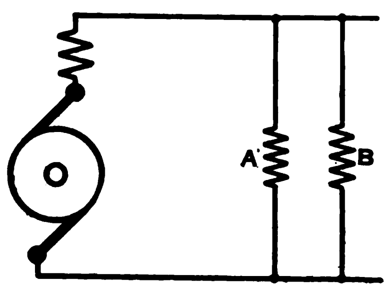


FIG. 355.

increase the current. As this current flows through the series winding, more flux will be produced and the voltage will rise.

It will be observed that lowering the external resistance on these two machines affects the voltage in the two cases in an exactly opposite sense. In the **shunt machine** the **voltage falls** while in the **series machine** the **voltage rises.**

Flat Compounded Machine

Now it is entirely possible to design a machine with two windings, one in shunt with the armature and one in series with the armature, so proportioned that to whatever extent the voltage tends to fall, due to the inherent properties of the shunt machine, this tendency will be exactly counter-balanced by the series winding, which tends to raise the voltage. This is the arrangement of a compound machine, Fig. 356, which has the shunt winding, *Sh*, and the series winding, *Se*. This machine is primarily a shunt machine. That is, the shunt winding is designed to produce the entire flux for the required voltage at no load. When the load is

applied, the current flows through the series winding, which contains the necessary ampere turns to generate enough additional flux to make up the voltage losses on the shunt side of the machine. Thus, if a current of 20 amperes is drawn, the loss of 2 volts which may be encountered in the armature, together with the tendency of armature reaction to reduce the flux, is compensated for by the added magneto-motive-force of the series winding, which produces enough additional flux to compensate for these losses. One of the three losses encountered in a shunt machine, namely, the reduction of current in the shunt winding, is not encountered in the compound machine, for by maintaining the terminal potential constant the shunt winding is made to exert its full strength at all times. There is, however, an added

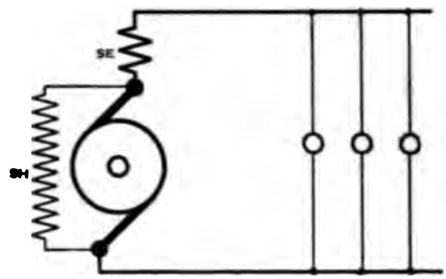


FIG. 356.—Short-shunt compound machine.

loss encountered, the resistance of the series winding. This winding then in a compound machine compensates for three losses. First, that due to armature resistance. Second, that due to armature reaction. Third, that due to the resistance of the series winding.

The series winding automatically supplies the proper ampere-turns required for any particular load. Thus, if the load is light, the armature drop and reaction are small. The current in the series winding is then small and the compensation small. If the load is heavy the armature drop and reaction are both high, but the current in the series winding is correspondingly great and the added ampere-turns thus automatically supplied exactly offset the loss, and the machine may be proportioned so as to maintain a constant potential at all times and under all variations in load. When so designed the machine is said to be **flat compounded.**

If the shunt field is connected across the brushes as in Fig. 356, it is called a **short** shunt compound machine. If the shunt field is connected across the terminals as in Fig. 357, it is called a **long** shunt compound machine. If a machine is to be excited from the switch board bus bars, the long shunt connection is preferred, for the connection directly to the positive brush *B*, Fig. 357, is not often carried to the switch board. The more common practice, however, is to use the short shunt compound connection. This tends to maintain the shunt field current more nearly constant on variable loads, as the drop in the series winding is not encountered by the shunt field current.

Overcompounded Machine

The series winding may be so proportioned as to **more** than compensate for the losses encountered on the shunt side of the machine. Instead of maintaining the voltage constant under variations of load, it is possible to actually raise the voltage as the load increases. When the voltage rises as the load in-

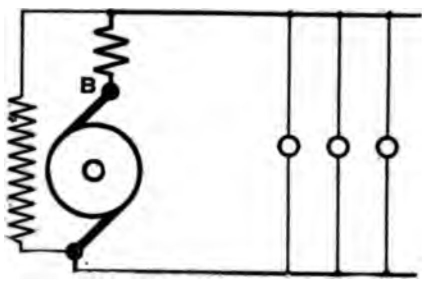


FIG. 357.—Long shunt compound machine.

creases, the machine is said to be overcompounded. If the voltage falls with the addition of the load, the machine is said to be undercompounded. Modern machines are usually overcompounded 10 or 15%. This permits the maintenance of a constant voltage at a center of distribution some distance away from the generator, the compounding taking care not only of the internal losses in the machine, but also the drop in the feeder supplying the load. A machine may be overcompounded to care for almost any desired feeder loss. Furthermore, the compounding may be adjusted. If a machine is overcompounded 10% and it is desired to reduce the compounding, a low resistance shunt strap,

T, may be placed in parallel with the series winding Se, Fig. 358. This divides the load current and reduces the compounding. If the shunt strap is equal in resistance to the series field, the current would divide equally. If the load current was 100 amperes and the machine overcompounded 10% without the shunt T, then when the shunt was put in circuit the compounding

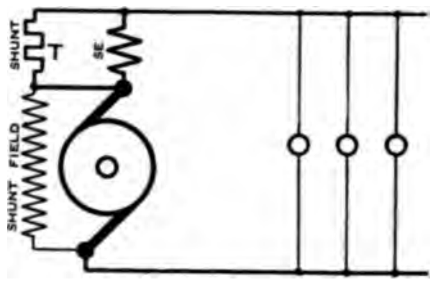


FIG. 358.

would be reduced to approximately 5%. By varying the resistance of the shunt, the compounding can be varied from the maximum downward to any desired extent. Obviously the compounding could never be raised, except by the addition of more series turns.

The series winding of a compound machine is located on the same cores with the shunt winding, Fig. 359, a place being re-

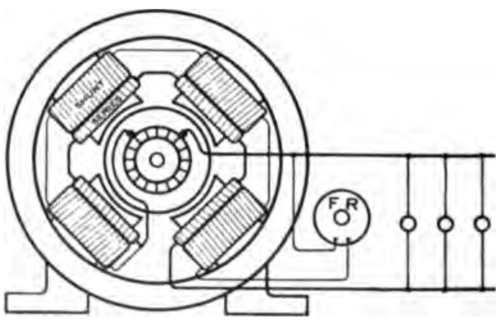


FIG. 359.—Illustration showing location of series and shunt windings, multipolar generator.

served for it in the design of the machine. If near the pole face, it is sometimes claimed that its close proximity to the armature enables it to more quickly bring about changes in field flux and

thereby regulate more closely. If back near the yoke, where there is more room, better ventilation is obtained.

A compound machine will maintain the desired voltage only at approximately the speed for which it is designed.

1. Compound wound generators, if designed for flat compounding, will overcompound if operated at normal voltage and an increased speed or if operated at normal speed and a reduced voltage.

2. Compound wound generators, if designed for flat compounding, will undercompound if operated at normal voltage and a reduced speed or if operated at normal speed and an increased voltage.

The effects noted above are due fundamentally to the change in relative number of ampere-turns in the shunt field regardless of saturation of the magnetic circuit and are fundamental in importance.

These effects are modified in commercial machines by the change in flux density in the magnetic circuit, which effect is incidental.

Assume a machine having a very low flux density, i.e., the saturation curve is a straight line. Assume that the shunt field has 1,000 turns and carries 1 ampere. The flux furnished by the shunt field would be proportional to 1,000 times 1 or 1,000 ampere-turns.

Assume that the series field has 10 turns and that the full load current of the machine is 10 amperes. The flux furnished by the series field would be proportional to 10 times 10 or 100 ampere-turns.

Assume that the speed of the machine is doubled and the no-load voltage maintained normal by adjustment of the shunt field current. The shunt field current will be halved and the ampere-turns in the shunt field halved as 1,000 times 0.5 is 500 ampere-turns.

Since the full load current remains the same, the ampere-turns in the series field are the same as before (100).

The per cent ampere-turns in the series field in the first case is 1,100 divided into 100 times 100 or 9.1% approximately. The per cent ampere-turns in the series field in the second case is 600 divided into 100 times 100 or 16.7% approximately. In other words, the machine becomes an overcompounded machine in the second case, because of the increase in the percentage of the total ampere-turns represented by the series ampere-turns.

If the machine is operated at normal speed but with a reduced voltage, the current in the field will be reduced in the same way and with the same effect. Half voltage and normal speed gives the same effect as double speed and normal voltage.

In the case of a flat compounded machine operated at reduced speed, the converse operation is true; that is, it undercompounds.

All the previous statements assume a straight line saturation and indicate the fundamental reason for the effects noted, being true for any machine.

Since all commercial D. C. machines must be operated at or near the knee of the saturation curve for stability of operation, the pre-emption of the magnetic circuit by the constant shunt field flux alters the effect of the series ampere-turns in two ways:

First.—In the case of the first statement the magnetic circuit is worked at a lower density and consequently the series ampere-turns become more effective. This increases the effect noted in a machine with a straight line saturation curve. The converse is true for the second statement.

Second.—A machine would have a straight line characteristic (external) if its magnetic circuit were worked on the straight line section and if there were no armature reaction. The fact that the field is worked above the straight line section contributes to the curved shape of the external characteristic curve. This is more pronounced in the case of the second statement, due to the higher saturation of the magnetic circuit. Armature reaction also modifies this shape in a manner dependent on the design of the machine but always tending to droop the curve on the lower flux density.

In consideration of the above statements it should be observed that the change in ampere-turns is fundamental and primary in consideration and **always** present, while the change in saturation is secondary and incidental and dependent on the design of the **individual** machine.

Also it should be remembered that a compound machine is ordinarily designed so as to work at a lower point on the saturation curve than a shunt machine of the same speed and voltage, i.e., at no load the magnetic circuit is worked below the knee of the curve. This is especially true of compound wound exciters for Tirrill regulator operation in which case the machines are

usually worked on the straight line section for a considerable range.

Multipolar Machines

The magnitude of armature reactions to be dealt with vary inversely as the number of poles in the field, therefore there is an advantage in multipolar machines as compared with bipolar. Very small machines are more economical to build if bipolar construction is employed. At about 5-kilowatt capacity, the cost is approximately the same for multipolar and bipolar construction. In larger sizes the advantage of multipolar construction becomes more pronounced. Very large bipolar machines are prohibitive in cost, and sparking at the brushes may be almost

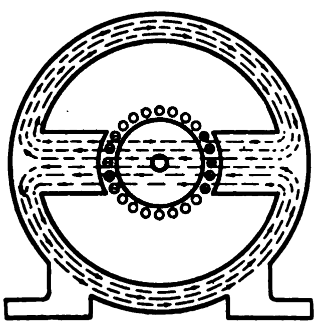


FIG. 360.

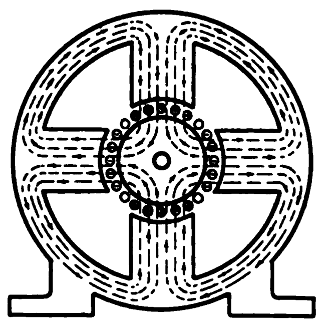


FIG. 361.—Flux distribution in 4-pole machine.

incurable. Multipolar machines can be made in very large sizes. The cost of construction is not out of proportion to the increase in size and commutation can be successfully cared for in every case.

Consider the length of the magnetic circuit in the bipolar construction, Fig. 360. To build machines of this type of twice the output it is evident that the length of the magnetic circuit would be considerably increased. The cost of material might, in large sizes, be more than double.

Now consider Fig. 361. The output of a multipolar machine may be doubled by doubling the number of poles. This would obviate the necessity of increasing the length of the magnetic circuit at all. The bipolar machine would have be to increased in length parallel to the shaft as its output increased. The

length of the multipolar machine need not be materially increased parallel with the shaft no matter how large the size.

As the number of poles and consequently the number of paths through the winding increases, the current per path for a given output diminishes, while the flux per pole for a given e.m.f. does not alter, regardless of the number of poles. This smaller current disturbs the fixed field strength less and less as the number of poles is increased. Hence, armature reaction diminishes and commutation improves. The shorter magnetic circuit in multipolar machines reduces the ampere-turns and the iron in the field materially. The ventilation is better because of the larger diameter and shorter length, hence such machines run cooler. Multipolar construction admits of shortening the length and increasing the diameter without the loss of efficiency and with a decided gain in mechanical construction.

The terminal resistance of an armature winding is expressed by the following formula:

$$R = \frac{r}{p^2}.$$

Where R = Terminal resistance of armature from all the positive brushes in multiple to all the negative brushes in multiple.

p = number of paths through winding.

r = total resistance of all the wire on the armature taken as one length.

Suppose an armature is wound with a thousand feet of No. 10 wire. This would have a resistance of about 1 ohm. Suppose it to constitute a 4-pole parallel winding. The brushes divide the armature into 4 paths, each of which will consist of $\frac{1}{4}$ of the 1,000 feet, or 250 feet, which would have a resistance of $\frac{1}{4}$ of an ohm.

As the brushes place the four sections in parallel, the combined resistance would be $\frac{1}{4}$ of $\frac{1}{4}$, or $\frac{1}{16}$ of an ohm.

Thus,

$$R = \frac{1}{4^2} = \frac{1}{16} \text{ ohm.}$$

SECTION VIII CHAPTER X

DIRECT-CURRENT GENERATORS

COMPOUND WOUND GENERATORS; MULTIPOLAR MACHINES

1. What are the three causes of drop in potential in a shunt generator as it takes its load? How may this drop be minimized?

2. If the external resistance is reduced upon a series generator with an unsaturated field and low armature reaction, what is the result upon the generated voltage?

3. If a generator is provided with both series and shunt field windings connected to aid each other, what will be the effect upon the external voltage when the resistance of the external circuit is reduced?

4. Explain in detail the regulation of a flat-compounded generator. Sketch.

5. Sketch a short-shunt or compound generator. Sketch a long-shunt compound generator. What are the relative advantages of the two methods of connection?

6. Explain the construction of an over-compounded generator. What are its advantages?

7. How may the compounding of an over-compounded generator be altered?

8. If a flat-compounded generator is operated at normal voltage and at a speed above normal, what will be the effect upon the compounding? Why?

9. If a compound generator is operated at normal voltage and reduced speed what will be the effect upon the compounding? Why?

10. What is the effect of various degrees of field saturation upon the compounding of a generator?

11. What are some of the advantages of multipolar construction over bipolar construction in generators?

12. Are multipolar machines cheaper to build than bipolar machines? If so, in what sizes?

13. Give the formula for the brush-to-brush resistance of an armature. Tabulate the meaning of each letter.

14. If a two-circuit armature winding in a six-pole field contains 1500 feet of number 8 wire, having a resistance of 0.64 ohms per thousand feet, what is the brush-to-brush resistance?

SECTION VIII CHAPTER XI

DIRECT-CURRENT GENERATORS

CHARACTERISTIC CURVES; EFFICIENCIES

Various characteristic curves of generators are taken to show the quality and degree of saturation of the iron in the field structure, the resistance of the armature winding and the regulation of the machine.

Field Saturation

The internal characteristic, or field saturation curve, of any machine is employed to show the degree of saturation at which the iron in the field is operated and the effect of varying field excitation upon the flux. Fig 362 shows such a curve for a shunt machine. Fig. 363 shows a diagram of connections for obtaining the data with which to construct the curve. Here the armature G of the generator under test is driven by a motor at a constant speed. A voltmeter, V, is connected across the brushes, and the field F is connected to an independent source of supply, C-O, in series with rheostat R and an ammeter A. A voltage may be observed with the generator running and no current in the field, which will be due to the residual magnetism only. A small current is now admitted to the field and the corresponding voltage noted. The field strength is gradually increased and for every increase in current the corresponding armature voltage is recorded. The curve is then constructed by plotting the armature volts as ordinates against the field amperes as abscissas. This gives a curve of the form V-K-C. It will be noticed that this curve does not begin at O but somewhat above the line of zero volts when there is no field current. This is due to the residual magnetism. It will be seen at a glance that the curve is practically a duplicate of the permeability curve obtained in the testing of iron. There magnetization, B, was plotted against magnetizing force, H. Here armature voltage, which is directly proportional to the magnetization, is plotted against field amperes, which are directly proportional to field ampere-turns, which constitute the magnetizing force. The ratio of armature volts to field amperes, then, is the same as the ratio of magnetization to magnetizing force which is permeability. The field

saturation curve, then, is a permeability curve of the iron in the field. If the curve rises abruptly and then bends over sharply it indicates high permeability worked well up to the saturation

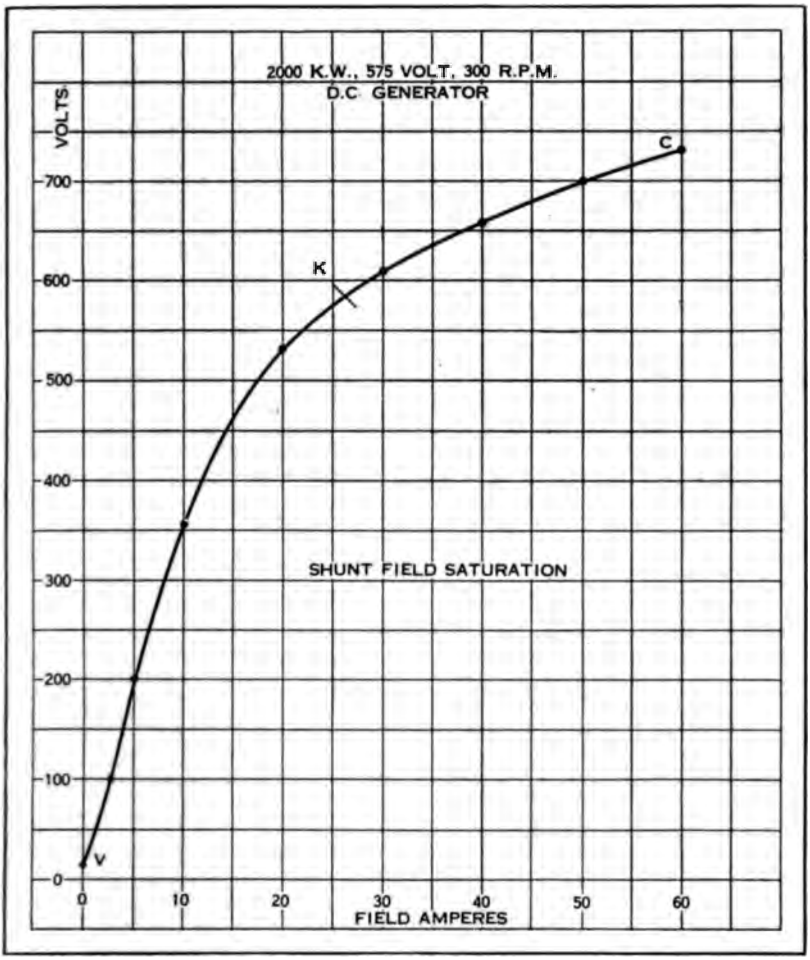


Fig. 362.—Field saturation curve for shunt generator.

point. If the curve rises more gradually and does not bend much toward the horizontal, less permeability and a lower saturation are indicated. If 110 volts is obtained in Fig. 362 at the point *C*, it is evident that the iron is well utilized in the

machine under test. If, however, the normal voltage was obtained at the point K, it would be an indication that the iron was not sufficiently saturated. That is, the addition of ampere turns on the field structure would permit of a reduction in the amount of iron required.

External Characteristics

The external characteristic shows the relation of the delivered volts to the current absorbed by the load. Such a curve of a shunt generator is shown at A-D, Fig. 364. The connections for obtaining it are illustrated in Fig. 365. Here the machine is operated at constant speed, starting with normal no-load voltage. The machine may be gradually loaded on a water rheostat, R, and

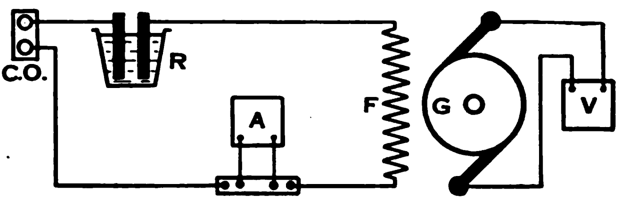


FIG. 363.

the value of the delivered voltage noted for every increase in load current, indicated as on ammeter A. The delivered current is plotted as abscissas and the corresponding terminal voltage as ordinates for the various points on the curve. The droop in the curve A-D, Fig. 364, is due to the three causes already noted, armature resistance, armature reaction and loss of shunt field current due to the first two causes.

The loss of voltage due to armature resistance, called the **internal loss characteristic,** is shown at E-F. As this is due to a fixed resistance, E-F will be a straight line. Connections for obtaining this curve are shown in Fig. 366. Here current from an independent source is led through a rheostat R and through the armature of the generator immediately after it is shut down and while it is still hot. The drop in potential for every increase in current is noted. Really, but one or two observations are necessary to get the loss, after which a straight line may be drawn from the point E through any point corresponding to a given external current and observed drop. By adding the ordinate F-G to the ordinate D-G, an ordinate C-G will be obtained.

Adding at various points the ordinates of E-F to those of the curve A-D, points may be obtained on which to construct the curve A-C. This gives the **total characteristic** voltage curve of a shunt machine; that is, it shows the generated voltage plotted against the total armature current which includes that

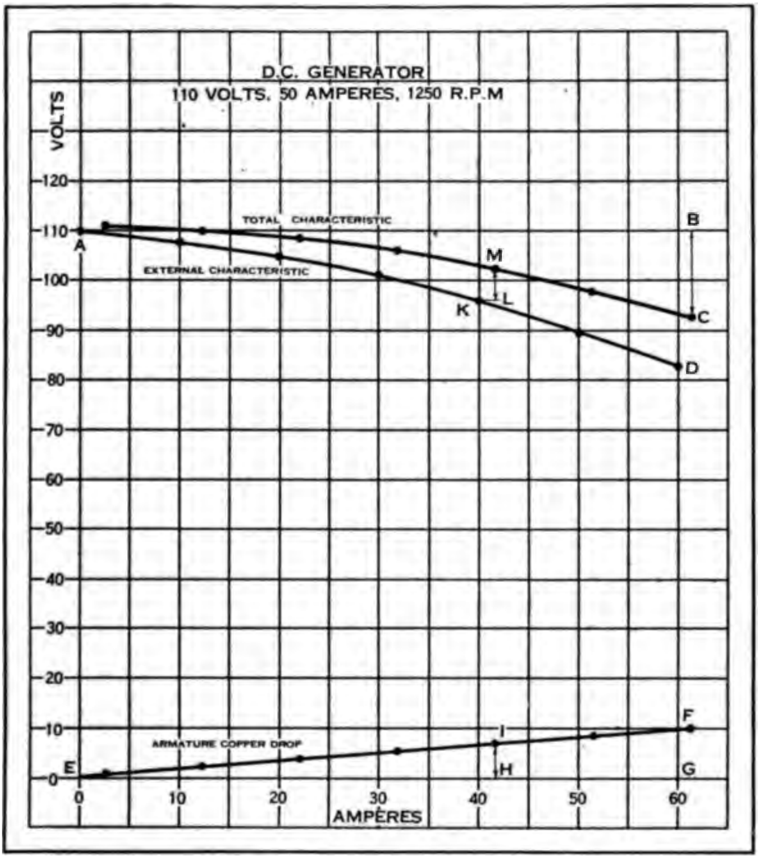


Fig. 364.—External characteristic curve of shunt generator.

taken by the load and that absorbed by the field. The fall in the generated potential from the theoretical point B to the point C is due to the effect of armature reaction on the field flux and a still further loss of field magnetism due to loss of field current, caused by the drop in potential at the brushes. To actually construct this total characteristic, the internal loss

ordinate, I-H, should be erected on top of the curve A-D, not at the point K, but at the point L, for the drop in the armature is produced not only by the load current but by the combined effect of the load current and the field current. This brings the proper point on the total characteristic at M.

If the external load is increased indefinitely, the external characteristic of a shunt machine drops first from A to B, Fig. 367, and then drops more rapidly to the point X. If the external resistance is lowered still further, the machine suddenly unbuilds, voltage and amperage falling rapidly to zero. This particular resistance at which the voltage and amperage fall is called the **critical external resistance** for the machine. Referring to Fig. 367, it will be noted that as the load is increased the brush poten-

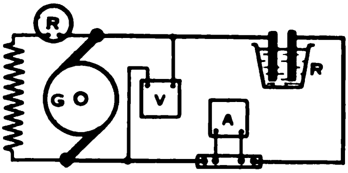


FIG. 365.

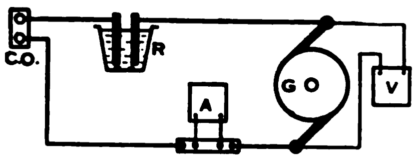


FIG. 366.

tial falls. This is equivalent to a reduction in the field excitation. As long as the excitation of the iron is above the knee, K, Fig. 362, considerable change in the field current produces comparatively small changes in field magnetism. When the critical external resistance has been reached, however, the voltage impressed upon the field lowers the excitation to the point K or below. Thereafter a slight change in field excitation produces a large change in field magnetism, so that any attempt to lower the external resistance beyond this point is accompanied by such a reduction in field current that the flux falls very rapidly. Load current and delivered voltage therefore continue to fall and the machine drops its magnetism entirely and the output falls to zero.

Most modern machines are designed with such a low armature resistance, however, that they would probably burn out before this critical external resistance was reached. Hence, the curve is rarely taken for a shunt machine beyond the point B, Fig. 367, the extension for B-X-O being projected from the observed way in which the characteristic of the machine is curving.

The **field saturation** curve of a **compound machine** is taken in precisely the same way as that for a shunt machine. The external characteristic is obtained by loading the machine as shown in Fig. 368. The no-load voltage obtained is first observed. The output is then increased gradually until the machine is

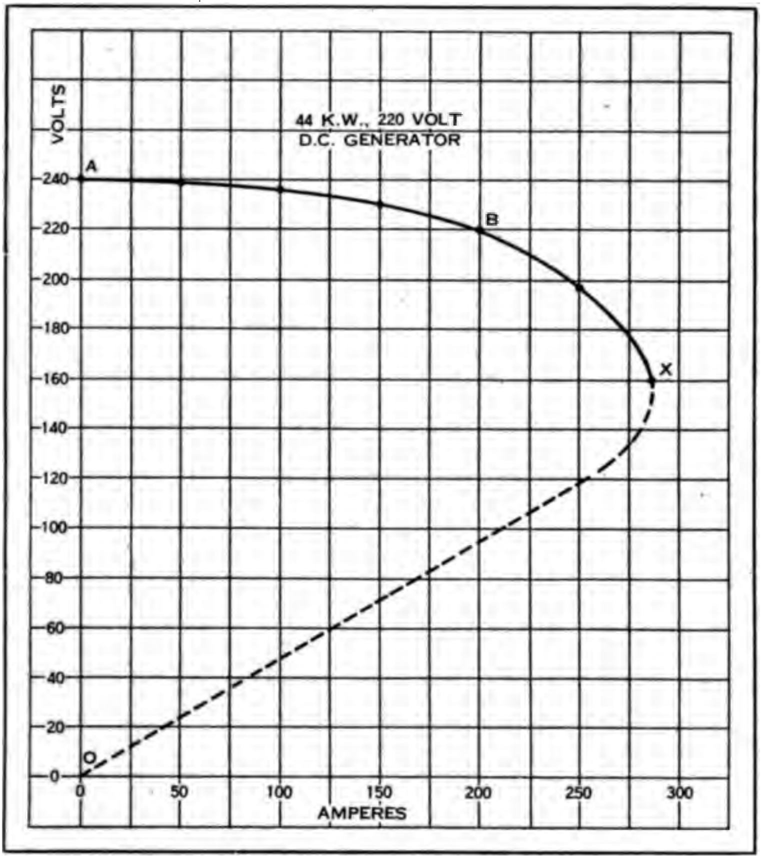


FIG. 367.—External characteristic curve of shunt generator.

delivering its rated full-load current and the corresponding values of voltage and current are noted. These will be plotted as shown in Fig. 369. Here the characteristic is *I-J-H*. This curve has a slight hump in the middle instead of being a straight line from *I* to *H*, as would be expected theoretically.

If the magnetic circuit had a straight line saturation curve and if there were no armature reaction, *I-J-H* would be a straight horizontal line. The **hump** is due to the decrease in ratio between magnetization and magnetizing force and to the fact that armature reaction increases somewhat faster than the armature current.

If now the series winding is disconnected and the line *L*, Fig. 368, is connected to the point *B*, an external characteristic for the shunt winding only may be obtained. This would give the curve *I-K*, Fig. 369. The difference between the shunt curve and the compound curve is evidently the e.m.f. furnished by the series winding. By subtracting the ordinate *G-K* from the ordinate *G-H*, the ordinate *G-L* would be obtained. A line drawn from *V* to *L* would represent the voltage furnished by the

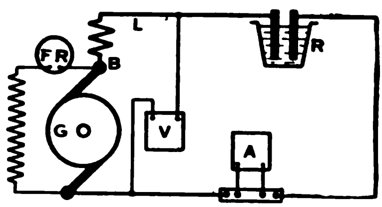


FIG. 368.

series winding throughout the variations of the external load. The series curve must thus be calculated. It cannot be constructed from observation because it is always produced by superimposing the series ampere-turns on top of a more or less saturated field, produced by the shunt winding. The series curve as thus obtained is not an accurate representation of the facts, however, for the effect of the machine's terminal voltage on the shunt field winding has necessarily been neglected.

Efficiencies

The purchaser of a generator is interested in the amount of power which the machine will deliver compared with that required to run it. If the machine absorbs 100 horse power at the pulley and delivers 90 horse power for useful purposes, it is said to have an efficiency of 90%. Efficiency is the **ratio of out-put to in-put**. It is expressed as a percentage of unity. It is always less than unity, for there is no perfect machine, no perfect transformer of energy.

Two kinds of losses are encountered in a generator, those on the mechanical side and those on the electrical side of the machine. The efficiency may therefore be analyzed so that the mechanical losses are involved in one expression and the electrical losses in another.

The gross efficiency of a generator is the ratio of the power

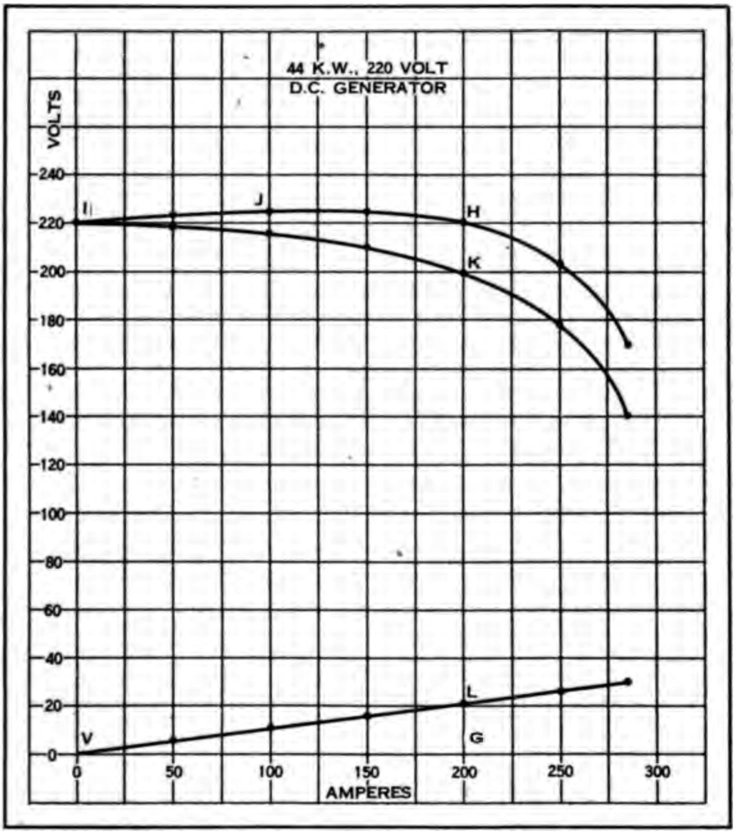


FIG. 369.—External characteristic curve of a "flat-compound" generator.

generated to the power absorbed. This is sometimes called the **efficiency of conversion.** If a machine absorbs 1,000 watts and generates 900 watts; $\frac{900}{1000} = 90\%$ gross efficiency. Deducting the generated watts from the absorbed watts, 1,000 minus 900 equals 100 watts lost. This lost power is distributed in the

following ways: Eddy currents, hysteresis, friction of bearings, friction of brushes and air friction. The designing engineer will examine each of these losses to see if it can be reduced. If the laminations of the armature core are not well insulated or if they are too thick, the eddy current loss will be high. If the iron is worked at too high a flux density or if it is not pure, the hysteresis loss will be large. If the bearings are not well designed, or if the oiling is poor, there will be considerable friction loss encountered. If the brushes are set with too much tension, excessive loss in friction will be encountered. If the surface of the armature is unnecessarily rough there will be windage to overcome.

The electrical efficiency of a generator is the ratio of the power delivered to the power generated. This is sometimes called the **economic coefficient.** If the machine delivers 810 watts for useful purposes out of the 900 watts which it generates in the armature windings, then $\frac{810}{900} = 90\%$ electrical efficiency. Two sets of electrical losses are encountered: The power required to overcome the resistance of the armature winding and the energy absorbed by the field to maintain the flux. Deducting the 810 watts delivered from the 900 watts generated leaves 90 watts lost in the two above mentioned places. The I^2R loss in the armature may be kept down by making the resistance low. The I^2R loss in the field may be minimized by making the reluctance of the magnetic circuit small, which in turn would require a small number of ampere-turns to maintain the flux.

The commercial efficiency is the ratio of the power delivered to the power absorbed. This is commonly called the **net efficiency.** In the machine under consideration, 810 watts are delivered out of 1,000 watts absorbed. Therefore $\frac{810}{1000} = 81\%$ commercial efficiency. Subtracting the 810 watts delivered from the 1,000 watts absorbed leaves 190 watts lost. This is divided between the two groups of losses above mentioned, 100 on the mechanical side, and 90 on the electrical side. It will be observed that the losses are about equally divided. This is quite common. The larger the machine, the less the total percentage of losses, but the electrical losses may frequently be about equal to the mechanical losses. It will be noted that

knowing the gross efficiency and the electrical efficiency, the commercial efficiency may be computed as above or by simply multiplying the first two efficiencies together. Thus, 90% gross efficiency multiplied by 90% electrical efficiency equals 81% commercial efficiency.

SECTION VIII CHAPTER XI

DIRECT-CURRENT GENERATORS

CHARACTERISTIC CURVES; EFFICIENCIES

1. Sketch a field-saturation-curve for a shunt generator. Analyze this curve, indicating the quality of iron which it represents. Indicate a point where 110 volts will be produced. State whether or not this represents a proper degree of saturation. What would be the effect of working the iron either above or below this point?

2. Give sketch showing connections for obtaining the data for a field saturation curve on a shunt generator.

3. Explain what data must be taken for plotting a field saturation curve and how it should be tabulated.

4. Sketch the external characteristic of a shunt generator. Indicate, at a certain point, the load current and corresponding terminal voltage. Indicate the no-load voltage. Analyze the curve in detail, pointing out its good or bad qualities.

5. Sketch the connections for obtaining the data from which to construct the external characteristic curve of a shunt generator.

6. What data should be taken in order to construct the external characteristic curve of a shunt generator, and how should it be tabulated?

7. Sketch the armature copper drop curve for a shunt generator. Mark thereon the voltage and current which would indicate a resistance of 0.05 ohms. How many separate sets of readings must be taken to obtain the necessary data for this curve? Analyze this curve and state what it indicates.

8. Sketch the connections for taking the armature copper drop curve and state what data is required.

9. Having sketched the external characteristic and the armature copper drop curves on the same sheet of cross section paper, proceed to accurately construct therefrom a total characteristic voltage-curve.

10. Analyze the total characteristic curve explaining in detail just what it means: just what losses are represented therein, and what losses are not represented.

11. What is meant by the "critical external resistance" of a shunt machine? What will be the effect of increasing the load beyond this point? Explain fully why this is so.

12. Sketch the external characteristic curve of a flat-compounded generator.

13. Analyze this curve, explaining the cause of the hump.

14. Sketch connections for obtaining the external characteristic of a compound-generator and state what data must be taken.

15. Upon the same cross-section paper sketch the characteristic curve for the shunt side of the foregoing compound-generator.

16. With the above two curves as a basis, accurately construct a series curve for the same compound-generator. Explain the relation between these curves.

17. Give the equation for the gross efficiency of a generator. State in detail the various losses that are involved.

18. Give the equation for electrical efficiency of a generator. State in detail the various losses that are involved.

19. Give the equation for the commercial efficiency of a generator. State in detail all of the losses that are involved.

20. A generator absorbs 10 h.p. from an engine and delivers 5 kilowatts The armature loss is 400 watts, the field loss is 600 watts.

(*a*) What is the gross efficiency?

(*b*) What is the electrical efficiency?

(*c*) What is the commercial efficiency?

DIRECT-CURRENT GENERATORS

TYPES OF MODERN D. C. MACHINES

The first successful generator for electric lighting was the Edison machine. This machine possessed a salient pole magnetic structure, Fig. 370. The keeper, K, and the pole pieces, P-P, were separate from the field cores, hence there were four breaks

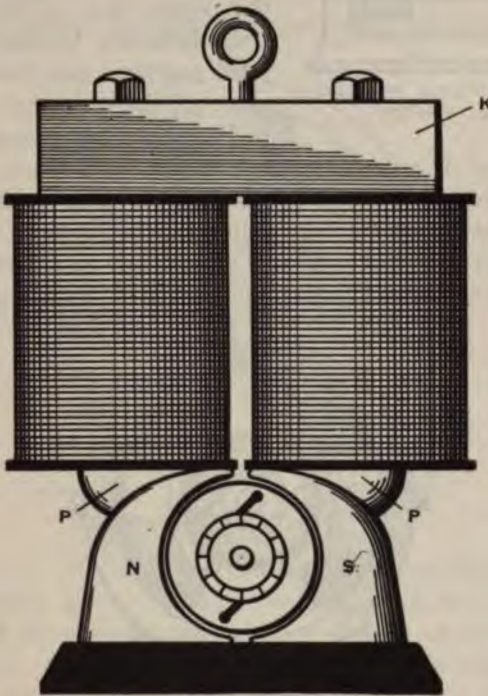


FIG. 370.—Old Edison bipolar machine.

in the magnetic circuit in addition to the air gaps. This involved considerable magnetic leakage. There was also a tendency for the magnetic flux to concentrate in the upper half of the armature, for magnetic lines always tend to contract. Nevertheless the machine was quite efficient in design and satisfactory in operation.

The next improvement was the type shown in Fig. 371. This was known as the iron-clad machine. A rectangular iron structure completely covered the field coils, which were placed on the cores very close to the armature. There were no breaks in the magnetic circuit and very few stray magnetic lines of force. As the field structure could be cast in one piece and the only machine work was that necessary to bore the poles for the armature, the design was an improvement over Edison's original machine. This machine has been modified more recently into the form shown in Fig. 372. By using a circular frame instead of a rectangular one, the field structure can be made to carry end brackets to support the bearings. This eliminates the bed plate and pillow blocks required to support the armature and makes a very economical and compact structure in sizes under a hundred kilowatts. Practically all manufacturers of bipolar machines today use the general form of field shown in Fig. 372.

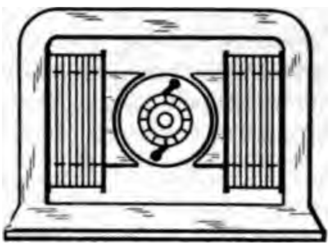


FIG. 371.—Original iron-clad bipolar machine.

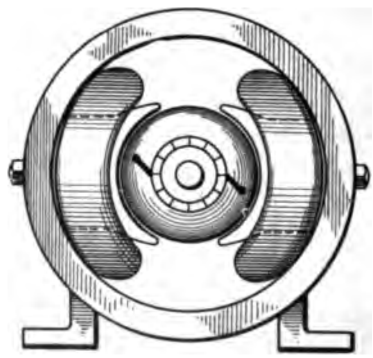


FIG. 372.—Modern bipolar machine.

Multipolar machines are standardized along the lines indicated in Fig. 373. The diameter and number of poles may be advantageously increased in proportion to the size. The length of the machine need not be increased to any extent. In fact, the net length of the largest size armature is rarely more than 18 inches,

and is fixed by the permissible diameter of the field core. Field cores cannot be well saturated if they possess a diameter much greater than 15 or 18 inches.

Where a large current is required at a low voltage, a very simple machine with a solid metallic disc for an armature and no commutator may be employed. This is the so-called **unipolar** or **homopolar** or **acyclic machine.** Fig. 374 represents a machine of this type designed by Forbes. Here a copper disc, *G*, about 30 inches in diameter, is mounted so that it projects between the poles of an electro magnet, *H-K*, circular in form, energized by a magnetizing coil *C*. The flux crosses this disc in the same direction throughout its entire circumference, as shown by the

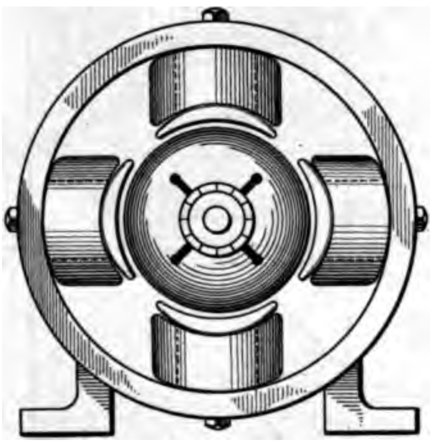


FIG. 373.

dotted lines, *B*. At intervals around the circumference there are holes placed in the casting, through which brushes *D* are made to bear on opposite sides of the disc so as to deliver or collect current. Other brushes are placed so as to rest upon the shaft at *E*. As the flux crosses the disc in the same direction at all points, an e.m.f. will be generated radially when the disc is rotated, urging a current either toward the circumference or toward the axis, depending upon the direction of rotation. This current is collected at *E* and delivered through the external circuit and returned to the circumference via the brushes *D*. A disc, 30 inches in diameter, traveling at approximately 2,500 r.p.m., with the highest flux density practical, will generate

about 25 volts. The current, of course, is limited only by the cross section and, consequently, the resistance of the disc and external circuit. By making the resistance low, as high as 10,000 amperes may be produced. The disc is in effect a large number of radial conductors all connected in multiple.

All attempts to build unipolar machines with a number of discs connected in series have proved failures because it is

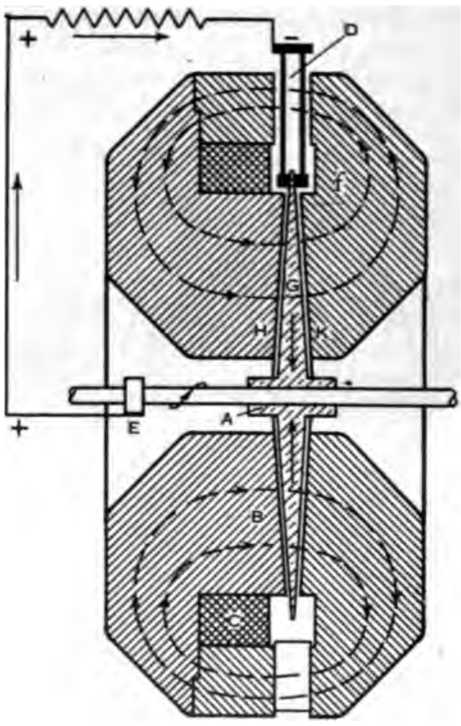


FIG. 374.—Principle of acyclic generator.

impossible to connect conductors in series without the connections themselves also cutting lines of force in a reverse direction, as the magnetic lines always form closed loops and an opposing e.m.f. would always be generated in the connections themselves, which would exactly neutralize the e.m.f. that otherwise would be obtained by a series connection.

Fig. 375 represents the principle of one of the acyclic machines built in this country. Here a revolving cylinder of iron, *A*,

carries on its surface 12 massive conductors, *a*, insulated from each other and from the core. Each of these conductors terminates in two slip rings, *C-C*. Magnetizing coils, *F-F*, supplied with current from without, send a flux across a small air gap between the stationary member, *B*, and the revolving member, *A*, to the center of the rotor, and thence radially outward through the conductors, *a*, to the frame and back again. As these loops of magnetic force radiate in every direction perpendicularly from the shaft through the conductors, *a*, it is evident that in

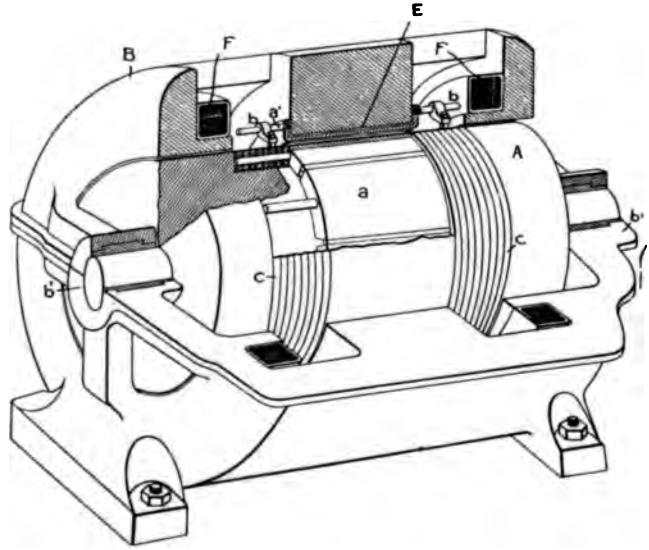


FIG. 375.—Noeggerath acyclic generator.

revolving, these conductors will cut said lines of force at right angles. There are 24 slip rings in all, two for each of the 12 conductors. On these slip rings rest brushes, *b-b*. As the current flows in the same direction in all of the revolving conductors, the reaction on the magnetic field is very great. The field is distorted, and the terminal voltage drops. To resist this effect, the current from each conductor is led back through a slot in the stationary member so as to produce a magnetizing effect equal in amount and opposite in direction to that produced by each revolving conductor. These are called frame conductors, and are shown at *E*. Through the brushes and frame

conductors the 12 active conductors, *a*, are connected electrically in series. Previous defects in securing sufficiently high speed for acyclic machines are very satisfactorily overcome by the use of steam turbines. The return of the current through the frame conductors neutralizes armature reaction. Nevertheless the great resistance due to 24 sets of sliding contacts in series involves a great loss and poor regulation. The mechanical defects encountered are such that the commutating machine is considered preferable to any form of acyclic generator, unless an output of very large current at very small voltage is desired.

Commutating Pole Generators

To insure sparkless commutation from direct-current machines, interpole generators have been devised. These machines

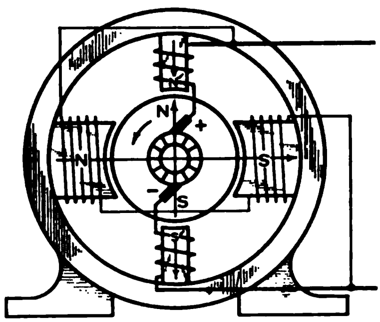


Fig. 376.—Connection of main and commutating poles on shunt generator.

have, in addition to the main poles, N-S, Fig. 376, auxiliary poles, N'-S'. The natural tendency of the armature of a generator is to distort the magnetic field. This was discussed under the head of armature reaction. The armature tends to develop a north pole under the positive brush in the figure, and a south pole under the negative brush. If, now, the current on its way out is led through an auxiliary winding on the poles N'-S', a counter magneto-motive-force will be established which resists the cross magnetizing effect of the armature. The poles N'-S' are very narrow and do not supply any of the main flux upon which the machine depends for the generation of its normal e.m.f. They contain a slightly greater number of ampere-turns than does the armature in the air gap region. As the interpoles

resist armature reaction and prevent field distortion, the brushes may rest on the theoretical neutral line at all times and need never be shifted. If a current of 10 amperes is passing through the armature the strength of the interpoles will exactly counterbalance and neutralize the distorting tendency due to this 10

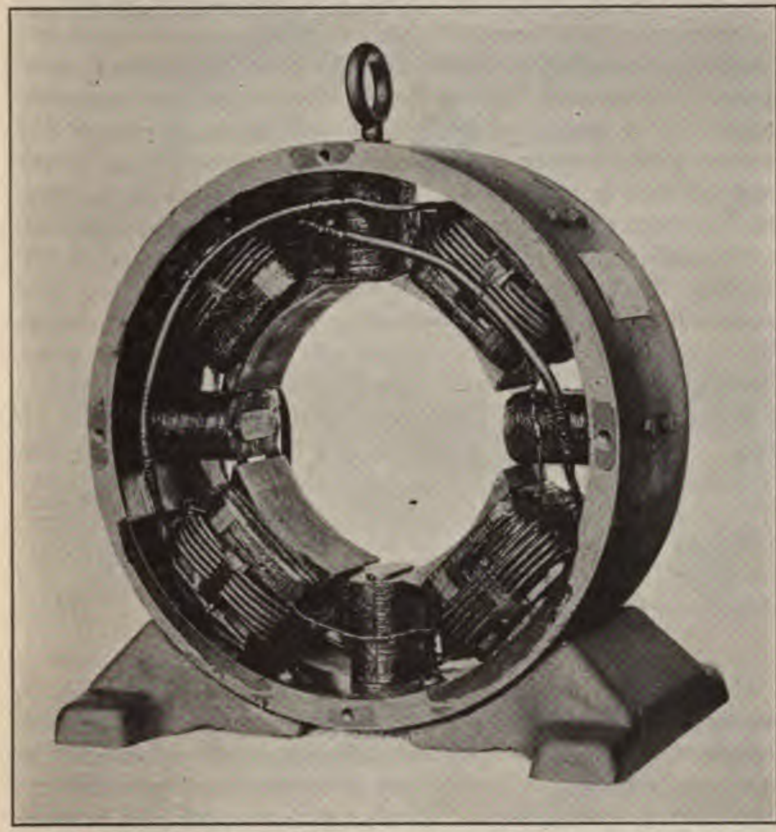


FIG. 377.—Westinghouse multipolar direct-current generator field structure with commutating poles.

amperes. If the current rises to 100 amperes the distorting tendency increases ten times, but as the interpole winding is in series between the armature and the load, the counter action is increased ten times and the main field flux remains practically undisturbed. Thus, no matter what the load, the brushes may always remain in the same position. In considering commuta-

tion it was observed that the brushes must be advanced in the direction of rotation so as to bring each coil under the tip of the pole, as it was short-circuited by the brush, so that the fringe of the flux might generate in the short circuited coil, the necessary voltage to aid in the reversal of the current. In the interpole machine, however, the excess of ampere-turns, placed on the interpoles, is sufficient to always produce a flux from the interpoles, through the short-circuited coil under the brush in an opposite direction to the tendency of the armature magnetization. This insures a flux which will actually reverse the current at the proper time in each coil, without regard to the fringe of flux from the main poles. If the load is 10 amperes the flux from the interpoles is small, and the voltage generated is just sufficient to reverse the 10 amperes. If the load is 100 amperes, the flux from the interpoles is ten times as strong, and there will be ten times the reversing voltage generated in the short-circuited coil, and the current will be built up to ten times the former value in the same time interval, during which the coil is under short circuit. This insures perfect commutation at all loads. The majority of moderate and large size direct-current motors and generators today are provided with interpoles. Fig. 377 shows the actual arrangements of the commutating poles and their position relative to the main poles in a multipolar generator, manufactured by The Westinghouse Electric and Manufacturing Company.

Three-Wire Generator

Most of the incandescent lighting from central stations in our large cities is done by the three-wire system. This system transmits power at 220 volts and utilizes it at 110 volts, resulting in a great economy in copper as will be explained in connection with wiring calculations. Edison, who devised this system, planned to use two 110-volt generators in series. To deliver 200 kilowatts would require two 100-kilowatt machines of 110 volts each. One-200 kilowatt machine would obviously be more efficient and less costly than two 100-kilowatt machines. To obtain 110 volts, however, from a single 220-volt armature would require that a brush be placed on the commutator midway between the main brushes. Between this brush and either main brush there would be just one-half the potential of the machine.

This third brush, however, would short-circuit a coil in the most intense field. Sparking would therefore be involved and abnormal heating of each coil would result, as it was short-circuited. A number of schemes have been devised for getting two fundamental voltages from a single commutating generator. Fig.

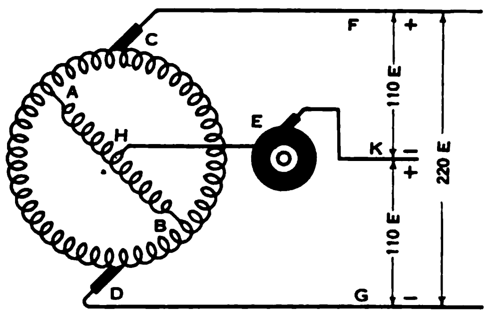


FIG. 378.

378 shows the plan adopted by one manufacturer. Here an ordinary direct-current armature wound for 220 volts is shown diagrammatically, from the commutator of which the brushes *C-D* lead the current to the external circuit. At two points, *A-B*, 180 electrical degrees apart, taps are taken from the armature winding or corresponding commutator segments to a reactance coil placed within the armature. This coil consists of copper windings on an iron core and is in effect a transformer with a single winding. Across this winding there is the full potential difference of the armature. The drop is inductive and a current may be taken from a fixed point anywhere along the winding. The winding is tapped at its middle point, *H*, and connected to a slip ring, *E*, which is placed on the end of the shaft. A brush from this ring connects to the neutral wire of the external system. This wire, *K*, is at mid-potential between the two outside wires *F* and *G*. At any instant it is negative with respect to *F* and positive with respect to *G*. Through the reactance or balance coil, *A-B*, an alternating current is main-

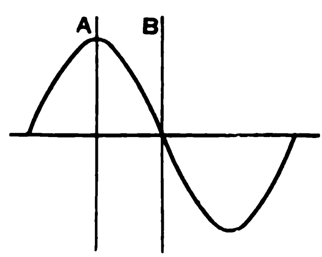


FIG. 379.

tained, for the current in the armature winding naturally alternates and it does not pass through any rectifying commutator to reach the balance coil. This current flows first in one direction and then in the other as shown in Fig. 379. At certain points in the rotation of the armature the current in the winding *A-B*, slip ring and neutral wire will die out entirely as indicated at *B*, Fig. 379. At other points the current will have its maximum value as at *A*. Thus, while the current in the wire *F* and *G* is not only direct, but continuous, the current in *K* is pulsating, having points of maximum and zero value. While this pulsation is not seriously objectionable for the operation of motors, where two fundamental voltages are wanted, it is often desired to have a more nearly continuous current in the neutral wire.

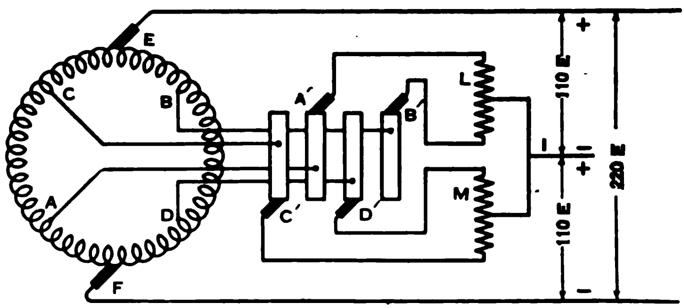


FIG. 380.

The connections for a later type of three-wire generator are shown in Fig. 380. Here, the armature is diagrammatically shown and from its commutator the brushes *E-F* lead current to the external circuit. At two points 180 electrical degrees apart, *A-B*, taps are taken to two slip rings, *A′-B′*. From these slip rings brushes convey the current to a stationary reactance coil *L*, mounted in an iron case external to the machine. At two other points 180 electrical degrees apart, *C-D*, and 90 electrical degrees from the points *A-B*, two other taps are taken from the armature winding, leading to slip rings, *C′-D′*. From these rings brushes feed a second balance coil, *M*. The middle points of both of these balance coils connect to each other and to the neutral wire *I* of the three-wire system. As the currents in the two balance coils are 90 electrical degrees apart as regards

the time when they are produced, when the current in one is zero, as in B, Fig. 381, the current in the other, A, is at its maximum value and vice versa. One or the other of the balance coils thus supplies the neutral wire with current at all times. The combined current from the two is more nearly continuous than that obtained from a single coil and slip ring. These machines

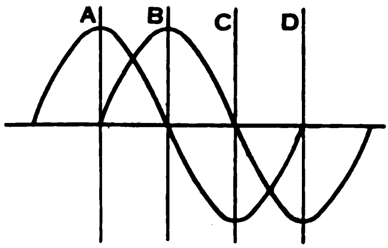


FIG. 381.

may be compound wound. If so constructed the current from the positive brush passes through the series windings on all the north poles on its way to the external circuit, while the negative brush is connected in series with the windings on all the south poles. This divides the compounding so as to more accurately maintain the potential on the two sides of the system. The

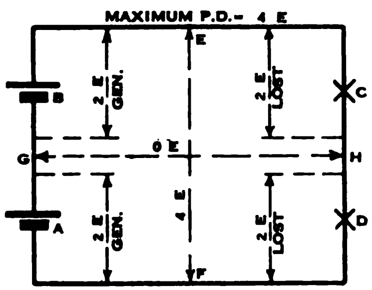


FIG. 382.

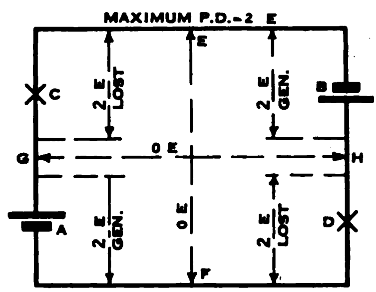


FIG. 383.

above outlined scheme permits two fundamental voltages to be obtained, one double the other, from direct-current commutating machines.

Brush General Electric Arc Light Generator

An unusual form of machine is the Brush General Electric Arc Light Generator. This machine furnishes six or eight thousand volts without subjecting the insulation of the machine or any

part of the system to a potential strain of more than 2,000 volts. The scheme involves a connection known as the "Brush multi-circuit device." The principle may be understood from a study of diagrams 382 to 385. In Fig. 382, consider two sources, *A* and *B*, of two volts each, in series. These supply a load consisting of *C* and *D*, likewise in series. The voltage generated by *A* and *B* in addition, is four volts. A voltmeter connected between *E* and *F* will measure the maximum potential generated by the source, which is 4 volts, and also the voltage lost in the load, which is likewise 4 volts. Across the points *G-H*, no potential difference will be found. This is because the voltage is raised as much in the source, *B*, as it falls in the load *C*. Now, consider a modification of the circuit, in Fig. 383.

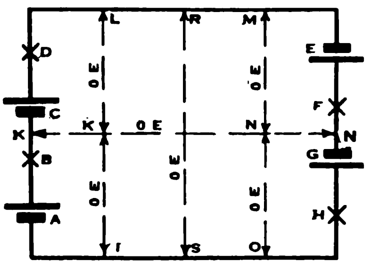


Fig. 384.

Here the sources of e.m.f. and the load are connected alternately. The source, *A*, raises the pressure 2 volts, and the load *C* absorbs this pressure. The source *B* raises the pressure again 2 volts, and the load *D* absorbs it, but as the pressure falls as much through *C* as it was raised through *A*, there will be no difference of potential between *E* and *F*, whereas before there was a maximum of 4 volts. There is no difference of potential between *G* and *H*, however, as before. It will now be seen that, while precisely the same work is accomplished in Fig. 383 as was accomplished in Fig. 382, the maximum strain to which the insulation of any portion of the circuit is subjected is only 2 volts instead of 4. Carrying this still further, consider Fig. 384. Here is a source *A* in series with a load *B*, a source *C* in series with a load *D*, a source *E* in series with the load *F*, a source *G* in series with the load *H*. As the current falls as much through *B* as it was raised in *A* there is no difference of potential between *I* and *K*. The same holds true for *K* and *L*, *M* and *N*, *N* and *O*. There will, therefore, be no difference of potential between *K* and *N*, and *R* and *S*. Thus, while a total of 8 volts is generated and utilized in the circuit, the maximum difference of potential that can be anywhere detected is 2 volts.

The Brush General Electric Arc Light Generator employs the above outlined principle. It consists of a multipolar generator with a Gramme ring armature, divided into four sections supplying four separate commutators. These commutators are connected alternately in series with street circuits of arc lamps as shown in Fig. 385. Here the current from commutator *D*, under a pressure of approximately 2,000 volts, is passed through the series field winding of the machine and thence to the external

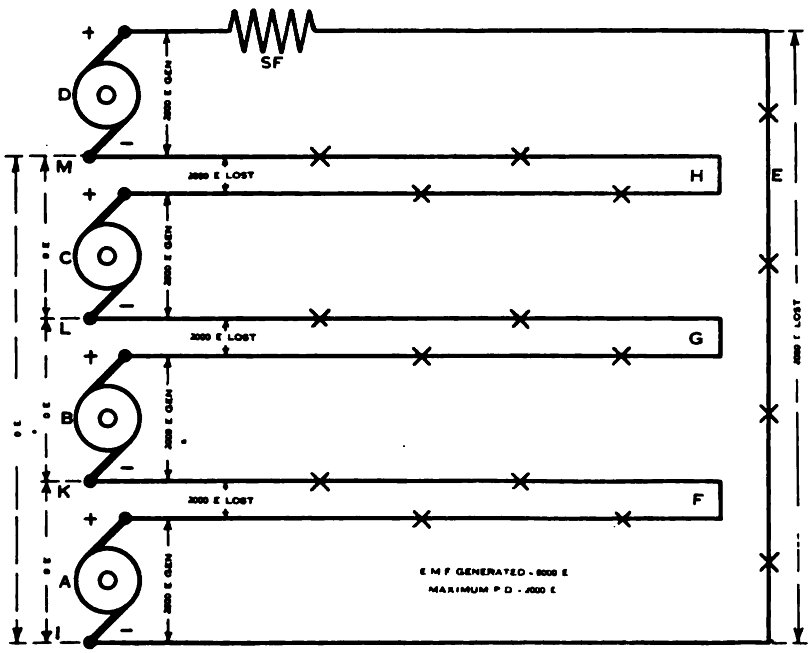


FIG. 385.

circuit *E*, where this pressure is absorbed. Returning to the machine, the commutator *A* picks up the current and raises the pressure 2,000 volts, whence it is led into the external circuit *F* and absorbed. Commutator *B* takes this current and raises it 2,000 volts and delivers it to the external circuit *G*. Commutator *C* again raises the current 2,000 volts and delivers it to the circuit *H*. As the voltage generated in each section of the armature is lost in an external circuit, before it is further raised in potential, it is evident that there will be no difference of

potential between the negative brushes, *I* and *K*. This likewise holds for *L* and *M*. With the load equally distributed between the various external circuits there will therefore be no difference of potential between any of the negative brushes. All of the positive brushes are similarly at the same potential. This means that the maximum potential difference anywhere on the machine and the maximum potential strain to which the insulation of the windings or the external circuit will be subjected is but 2,000 volts, whereas a total of 8,000 volts is generated and absorbed.

While there is no demand for this type of machine today, many are still in use. Arc light circuits are now commonly

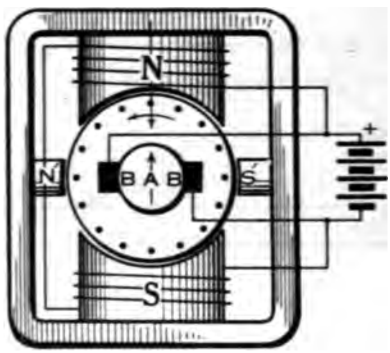


FIG. 386.

supplied from alternating-current generators of large capacity which at the same time supply current for incandescent lighting and power. The arc light circuits are supplied through transformers, which furnish a constant current in the series circuit, the current usually being rectified in order that the arc lamps may operate at maximum efficiency.

Variable-Speed Constant-Output Machines for Train Lighting, Automobile Charging, Etc.

Brolt Generator.—The Brolt machine is designed for furnishing a constant output over a wide range in speed. The armature, *A*, Fig. 386, revolves in the main field, *N-S*, which is connected in shunt with the brushes, *B-B*. The cross magnetizing force of the delivered current produces an auxiliary field across the

poles N'-S', which are not provided with a winding. The armature in revolving cuts this second field. Currents generated in the conductors under these auxiliary poles are short-circuited by extra broad brushes B-B. The magneto-motive-force of these short-circuited currents is diametrically opposed to the main field flux. If, now, the machine is delivering current to a storage battery and the speed is increased, the first effect is to increase the voltage and current output. Any increase in current, however, drawn from the brushes, B-B, is accompanied by an increase in the cross field. This causes an increase in the current generated in the coils on short circuit under the brushes, which in turn increases the opposing magneto-motive-force to the main flux. The actual flux crossing the armature from the

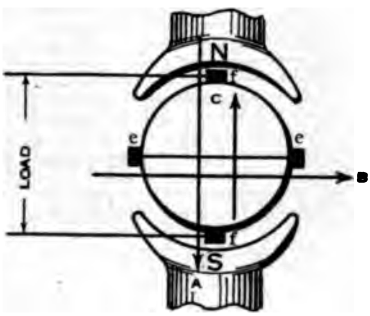


FIG. 387.

main poles, therefore, falls in direct proportion to the increase in speed. Consequently the voltage and current output remain fixed throughout a wide range of speed.

Rosenberg Generator.—The Rosenberg Generator is of an unusual design. It may be arranged: First, to deliver a constant current at a variable speed on a constant external resistance. Second, to deliver a constant output at a constant speed on a variable resistance.

The principle of this machine is illustrated in Fig. 387. It consists of a field structure having an unusually large polar span and a high flux density. It may be either series or shunt wound. There are three magneto-motive-forces to be considered. First, the main magneto-motive-force, which produces the flux, A. The revolving armature cuts this flux, and produces a current which is collected by the brushes, e-e, which are short-circuited

on themselves. The cross magneto-motive-force set up by this armature current produces a secondary flux, B, at right angles to A. The armature conductors cut this flux also and the load current is collected from brushes f-f, which are perpendicular to the secondary field. The magneto-motive-force due to the load current is in the direction C, which is diametrically opposed to the main field flux. It will now be evident that the machine is in a state of magnetic balance. Should the resistance of the external load be decreased, the current rises. The magneto-motive-force due to this current in the direction C now increases. This reduces the primary field flux, A. This in turn reduces the short circuited current across the brushes e-e. This reduces the

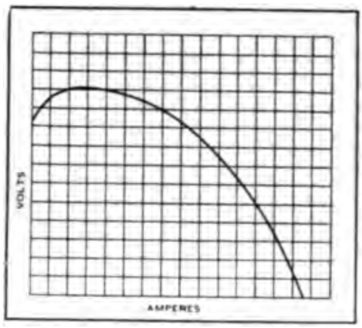


FIG. 388.

secondary flux, B, which in turn reduces the voltage of the load current, collected by the brushes f-f. It will thus be seen that the machine delivers a constant output when connected to a load of variable resistance, the voltage falling in direct proportion to the increase in current. The characteristic curve of such a machine is shown in Fig. 388. It is evident that the kilowatt delivery as indicated by this curve is practically constant at all points, for if the machine delivered 100 volts and 50 amperes, or 5,000 watts, a reduction of the external resistance so as to call for 100 amperes would be accompanied by a fall in potential to practically 50 volts, which would equal the same 5,000 watts.

A somewhat better idea of this action may be obtained from a study of the vector diagrams in Fig. 389. Here O-A represents the primary flux due to the main field. Opposed to this is the counter-magneto-motive-force, D-C, due to the load current.

The short circuited current across the brushes *e-e* produces the secondary flux *O-B*. The net difference between the armature's counter-magneto-motive-force and the main field is *O-C*. This combined with the secondary flux, *O-B*, at right angles thereto, gives the net resultant flux Φ, *O-E*. Should the resistance of the external load decrease, the conditions may be represented in Fig. 390. Here *O-A′* represents the field flux as before. The increased load current, however, lengthens the vector *D′-C′* in opposition thereto. The net difference, *O-C′*, therefore, falls. The short-

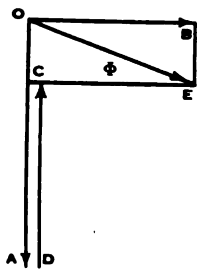


FIG. 389.

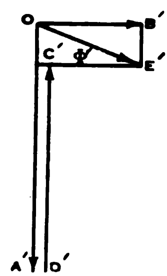


FIG. 390.

circuited current across brushes *e-e* will also fall. The flux due to this current, *O-B′*, likewise diminishes. The net resulting flux of the machine now likewise falls to Φ', *O-E′*.

This machine will deliver a constant current at variable speed if it is connected to a constant external resistance. Thus, if it is employed to charge a storage battery on a Pullman car, as in the axle generator system of train lighting, any increase in speed is accompanied by a slight increase in current. This current promptly reacts on the main field flux to reduce it. This, in turn, lowers the short-circuited current and the flux *B* produced thereby. This prevents any rise in terminal voltage. The net result is that the total useful flux of the machine is reduced in almost exact proportion, to the increase in speed. Consequently the machine supplies a constant voltage and therefore a constant current to a load of constant resistance over a wide range of speed.

Another application of the machine is for the operation of individual searchlights. Here it may be designed to deliver a constant output at a constant speed on a variable resistance.

The electric arc is a very unstable resistance. If the arc is shortened, as when the carbons are fed together, the increase in current results in a further reduction in the resistance of the arc. This tendency causes the current to rise abnormally upon a slight reduction in arc length. To check this tendency, searchlights are usually operated on constant potential circuits, with a ballast consisting of an iron wire resistance in series. Now, if the carbon electrodes approach each other, the rise in current through the resistor is accompanied by an increase in temperature therein. This causes an increase in resistance as the resistor possesses a positive temperature coefficient. This increase in resistance counterbalances the fall in resistance of the arc and makes the combined resistance practically constant. The

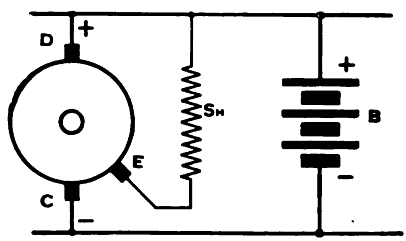


FIG. 391.

Rosenberg generator applied to a searchlight obviates the necessity for the use of a ballast, for when the resistance of the arc falls, from any cause, and the current starts to rise therein, this current, passing from the brushes, *f-f*, results in increasing the opposition to the main field flux *A*, which in turn reduces the short-circuited current and the secondary flux, *B*, resulting therefrom, which promptly lowers the terminal voltage of the machine. This drop in terminal voltage will evidently check any tendency for the current in the arc to over-run.

Bucking-Series Generator.—One of the earliest types of small generator for charging storage batteries on automobiles was the **bucking-series** machine. This was in effect a differentially compound generator, the series and shunt fields being connected to oppose instead of aid each other. An ordinary compound machine may be overcompounded so that the voltage will rise with an increase in current. Such a machine is called an overcompounded machine. If, now, the series field is reversed, the

voltage will fall as much for a given increase in output as it rose when the fields were in addition. By making the series winding relatively powerful it is possible to materially reduce the actual flux of the machine. The windings are so proportioned that when the speed of the engine rises, a slight increase in current output is accompanied by a sufficient rise in the strength of the series field to reduce the flux produced by the shunt field sufficiently to check any further increase in current. The windings are so proportioned that the machine delivers a practically constant output over a wide range of speed.

Third-Brush Generator.—A widely used generator for charging storage batteries on automobiles is the **third-brush** machine, Fig. 391. Here the main brushes, *D-C*, supply the storage battery, *B*, with current. The shunt field, *SH*, is connected between the positive brush, *D*, and a third brush, *E*. While this brush is in an active field the current which it is called upon to carry, only a little more than one ampere, does not cause any trouble from sparking. The resistance of the brush itself is sufficient to limit the current in the coils which it successively short circuits. Fig. 392 shows the actual arrangement of a generator of this type. Normally the field across the poles *N-S* is perpendicular to the plane of the main brushes, *D-C*. The e.m.f. between these brushes is about 7 volts. The shunt field winding is connected between the positive brush, *D*, and the third brush, *E*. The e.m.f. across these brushes is about 5 volts, which is sufficient to supply the field winding with about 1¼ amperes. If, now, the generator is increased in speed, the current output to the storage battery rises. Armature reaction sets in to distort the field into the position shown by the dotted lines, *F-S-N-G*. This obviously reduces the amount of flux between the brushes *D* and *E*. As this distortion increases approximately in direct proportion to the speed, the voltage delivered by the main brushes is practically constant at all speeds.

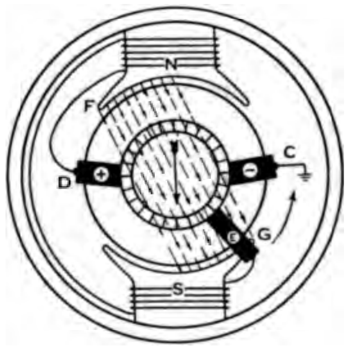


FIG. 392.—Principle of third brush generator.

A very slight adjustment of the position of the brush E serves to regulate the actual current output of the machine.

It will be evident that the "bucking series" and "third brush" types of generators should never be operated on open circuit, for as the speed rises the flux and voltage will rise indefinitely as there is no opposing current in the series field of the former to reduce the flux, and no armature reaction due to a load current in the latter. In the bucking series type the **field** may burn out. In the third brush type the **armature** may **also** burn out for the following reason: The brushes, D-C, are placed in a neutral position in the distorted field, therefore when the field is undistorted they short-circuit coils which are active. Without any armature reaction the voltage rises and this raises the flux so that the voltage generated in these short-circuited coils is sufficiently high to endanger them. Should it be necessary to disconnect the battery, which is supposed to be permanently placed across the terminals of either of these types of machines, the main leads of the generator should be invariably short-circuited. No harm will result from so doing, for the output is limited, when so short-circuited, to the current for which they are adjusted, whereas if they are left on open circuit the voltage may rise to such an extent as to burn out the windings.

SECTION VIII CHAPTER XII

DIRECT-CURRENT GENERATORS

TYPES OF MODERN D. C. MACHINES

1. Sketch an iron-clad bipolar direct current generator. What are its advantages?
2. Sketch a multipolar direct current generator. What are its advantages?
3. Sketch and explain the Forbes Acyclic generator.
4. Explain the principle of the Noeggerath Acyclic generator. Is it practical? Why?
5. Sketch and explain the principle of the commutating-pole generator. What are its advantages?
6. Sketch and explain the principle of the three-wire generator. What are its advantages?
7. Sketch batteries and lamps in a series circuit to illustrate the Brush General Electric multi-circuit device. What are its advantages?
8. Explain the Brolt constant output generator. Sketch.
9. Explain in detail the principle of the Rosenberg generator. What are its advantages? Sketch its external characteristic curve.
10. Explain the principle of the bucking-series generator. Sketch.
11. Explain the principle of the third-brush generator. Sketch.
12. What will be the effect upon the delivered voltage and current if the speed is increased on a Brolt, Rosenberg, bucking-series or third-brush generator when connected to a load of fixed resistance?
13. What will be the effect of operating a bucking-series generator at an increasing speed if the external circuit is open?
14. What will be the two effects of operating a third-brush generator at an increasing speed if the external circuit is open?

SECTION VIII CHAPTER XIII

DIRECT-CURRENT GENERATORS

PARALLEL OPERATION OF D. C. GENERATORS

Series, shunt and compound generators may be operated in parallel provided they are designed for equal voltages and have similar characteristics. There is little occasion to operate series generators in multiple. Shunt and compound machines are frequently so operated. There is an inherent tendency on the part of shunt machines of similar type to operate in parallel and divide the load in proportion to their capacities. If they are of equal capacities and the load for some reason becomes unequal, the more heavily loaded member will fall in voltage due to its greater load. This will cause it to let go of some of its

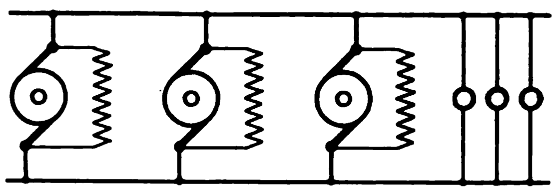


FIG. 393.

load. The machine with the smaller load naturally tends to rise somewhat in voltage. This makes it tend to reassume a portion of the load which the more heavily loaded machine has dropped.

If the machines are of different types, one a shunt interpole and another a shunt non-interpole machine, even though they may be designed for the same voltage and capacity they will not readily divide the load equally between them. This is because the interpole machine is usually a better regulating generator than the non-interpole, which would cause the former to take a larger proportion and the latter a smaller proportion of the increasing load.

Any number of shunt machines may be operated in parallel even though they are of widely different capacities. Fig. 393 shows such machines connected to a load. The actual arrangement of two machines for parallel operation with instruments and switches, is shown in Fig. 394. Assume G' to be carrying

the load, S' being closed. Ammeter A' shows the current output and V' the voltage of the system. When the load becomes greater than G' can carry, it is necessary to start up G. When it is brought to speed, the voltmeter V' may be disconnected temporarily from the mains by means of a plug switch and connected across the terminals of G. FR should now be adjusted until V indicates two or three volts above the line pressure. This is because the line voltage is that **delivered** by G', while V now indicates the **generated** voltage in G. The latter will fall as soon as G is connected to the line. Switch S may now be closed, care being taken to watch A. If this ammeter indicates backward, it shows that the voltage of G was not sufficiently high and instead of delivering current as a generator to help G',

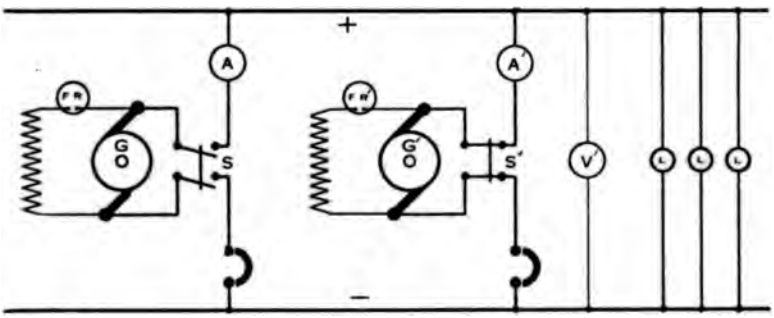


FIG. 394.—Diagrammatical connections of circuits for operating shunt generators in parallel.

it has become a motor, absorbing power from the line and imposing a still heavier load on G'. If A indicates in the proper direction, the load may be distributed between G and G' in proportion to the respective capacities of these two machines by simultaneously manipulating the rheostats FR and FR'. If the capacities are equal, and G delivers but 40 amperes, while G' continues to deliver 60 amperes, it is necessary to insert resistance in FR' which would lower the output through A' and at the same time cut resistance out of FR which would raise the output through A. In this manner the load could be divided equally. Should it be desired to transfer the load entirely from G' to G, the above-mentioned process should be continued, cutting resistance into FR' until A' indicates zero. When this ammeter reaches zero, S' should be pulled. This would take G'

off the line without arcing at the switch and without any strain on the system.

Compound generators of equal voltage and similar characteristics may be operated in parallel, but only with the aid of an **equalizer**. Should two machines be connected in parallel with-

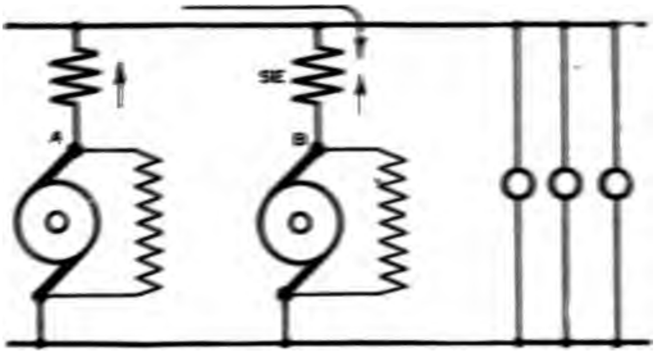


FIG. 395.

out an equalizer, as in Fig. 395, and if, from any cause, the voltage of *B* should momentarily fall, current from *A* would flow downward through *SE*, in the opposite direction to that which would make *B* compound. The series field would now act differentially with respect to the shunt and the voltage of *B*

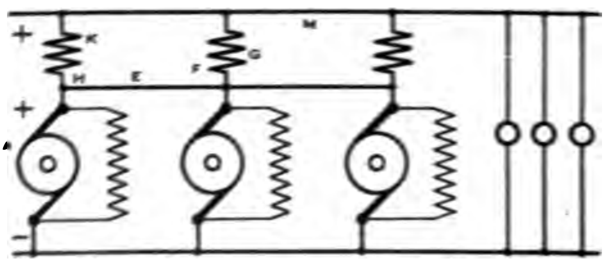


FIG. 396.—Location of "equalizer" for operating compound generators in parallel.

would rapidly fall. The increasing current from *A* would cause it to compound and in a few seconds *B* would motor, absorbing a large amount of current from *A*, which might damage both machines. To avoid such a possibility, an equalizer is provided as in Fig. 396. This is a massive copper conductor of low resistance which connects all the brushes of similar polarity to-

gether inside the series winding. As the series fields are usually on the positive side of the machine, this means that the positive brushes must all be placed in parallel, as are the negative brushes and also the positive terminals of the series windings. Now should the voltage of *B* tend to fall from any cause, current from the positive brush of *A* would flow through the equalizer to *F*, and thence in parallel with *K* through *G* to the positive bus. By holding the points *H* and *F* at the same potential through the medium of a low resistance equalizer, it is evident that the current from *A*, in order to reach the load, would never flow from *H* to *K* and thence backward through *G* and *F*, but must necessarily divide at *H*, part going up through *K* and part through the equalizer to *F* and thence out through *G*, where both portions would unite in the main bus bar, *M*, and pass to

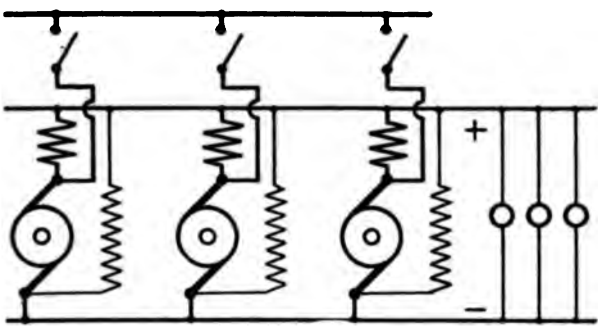


FIG. 397.

the load. It is thus impossible for the current in *G* to ever reverse as long as the equalizer is in circuit. The actual current which flows through *E* is usually small. Its low resistance insures that *H* and *F* shall always be maintained at the same potential, the slightest tendency of *B* to fall, being met by a flow of current through *H*-*E*-*F* which reinforces *G* and thereby helps to hold up the potential of *B*.

The inherent tendency of compound machines connected in parallel and provided with an equalizer to divide the load automatically in proportion to their capacities, is much more marked than in shunt machines. The equalizer is not often carried to the switchboard, but usually runs in a conduit beside the machines, each machine being provided with a single-pole knife

switch, often mounted on a pedestal beside it for the purpose of connecting a particular machine to the equalizer. This is shown in Fig. 397. Here only the positive and negative terminals of the machines are carried to the switchboard.

The order of procedure in placing compound machines in parallel is as follows:

First, start the machine G', Fig. 398, bring it up to speed, and adjust its voltage on V' to normal by rheostat R'. Next close S_2, then S_7, and finally S_6. S_2, S_6 and E' may be single-pole switches. A single-pole circuit breaker is usually inserted at S_7. The ammeter A' and circuit breaker must be

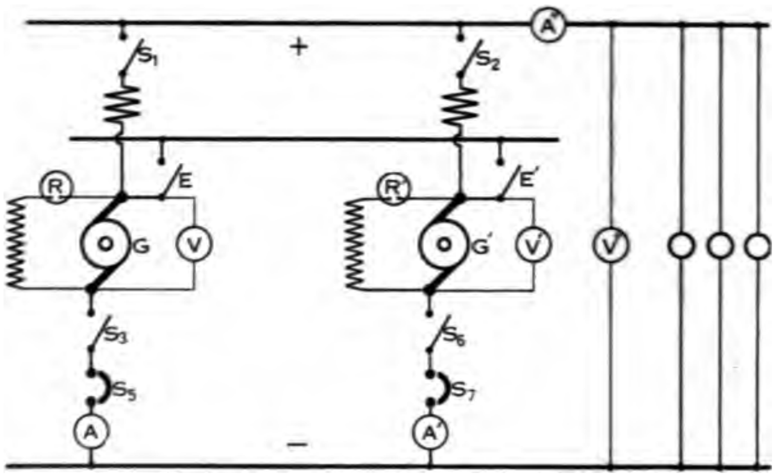


Fig. 398.—Diagrammatical connections of circuits for operating compound generators in parallel.

placed in the lead of the machine on the side opposite to the series winding, for only in this position will the entire current for this machine be shown and the operation of a single-pole circuit breaker disconnect the machine from the load.

When the load becomes too great for G' to carry, the second machine must be started. Proceed as follows: First, close E and E'. Now bring the machine up to speed and adjust R until V is approximately equal to V', then close S_1. This allows the current from G' to flow through E', the equalizer bus and E, and thence out through the field of the second generator, thus equaliz-

ing it before it is delivering any power. That is, its series and shunt field are excited and it is compounded as is G'.

A further adjustment of R may now be made to bring the voltage to that of G'. It is not so important to have its voltage exceed that of G' because of the fact that as these machines are compound, their voltages will not fall when they assume the load. Next close S_5 and finally S_3. The circuit breakers, S_5 and S_7, should be closed before the final switches, S_3 and S_6, so that they may open in case of excessive current due to defects in generator or poor judgment in paralleling. A will now indicate the portion of the load assumed by the second generator. The

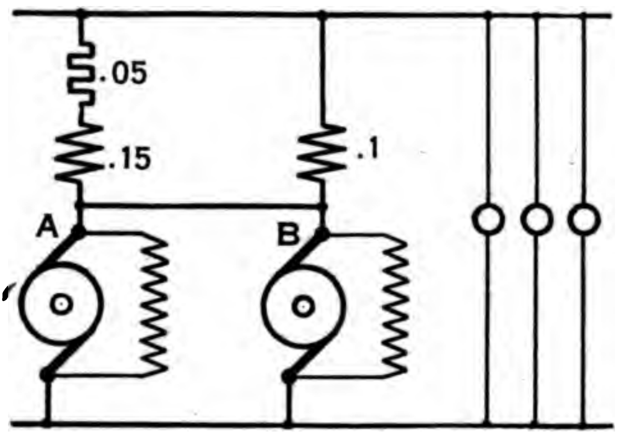


FIG. 399.

proper division of the load in proportion to the capacities of the machines may now be made by simultaneously manipulating R and R', as in Fig. 394. Should it be desired to disconnect G', proceed as follows: Cut resistance into R' gradually until A' shows zero. At this particular instant trip the circuit breaker, S_7, then open S_2, then S_6, then E' and shunt down G'.

Compound machines of different capacities may be operated in parallel provided, first, that they have similar characteristics; second, that they are of the same potential; and third, that they have series fields whose resistances are inversely proportional to the capacities of the two machines. Thus, suppose machine A, Fig. 399, of 25 kilowatts and 110 volts, is to be operated in parallel with machine B, of 50 kilowatts and 110 volts, the two

machines of course having their positive brushes connected by an equalizer. Now the load will divide automatically between these machines in proportion to their capacities, provided the resistance of the series field of A is twice the resistance of the series field of B, because the capacity of A is one-half the capacity of B. That means that if the resistance of B's series field is 0.1 R, the resistance of A's series field must be 0.2 R. If, now, A's series field had a resistance of only 0.15 ohm, it would be necessary to add a resistance of suitable current carrying capacity of 0.05 ohm in series therewith, as shown. This would establish the proper inverse ratio of series field resistance

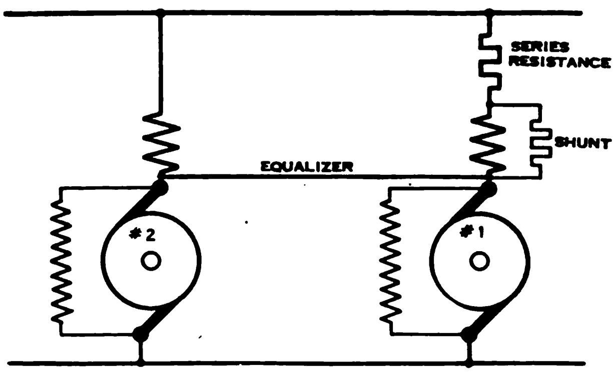


FIG. 400.

to the machines' respective capacities. Under these conditions a load of 30 amperes would automatically divide in proportion to the capacities, B assuming 20 amperes and A 10 amperes. A load of 75 amperes would likewise divide, 25 amperes coming from A and 50 amperes coming from B.

To produce a change in the compounding of an individual machine, the following procedure shall be adopted: Assuming that machine No. 1, Fig. 400, has a rising characteristic, i.e., is overcompounded, a shunt around the series field as indicated will bring the voltage to a flat characteristic if properly proportioned. Then taking **the series field and its shunt as a whole,** the resistance is compared with that of the series field of machine No. 2 (which is normally flat compounded) and adjusted by resistance in series to the proper relation, i.e., resistance inversely proportional to the capacities. If the resistance of the series field and its

shunt on machine No. 1, is lower than it should be, resistance must be added in series as shown in the diagram. It will be noted that the currents from the two machines will now equalize and that while that passing through the equalizer to machine No. 1 does not **all** go through the series field, the **correct proportion does** pass through that field to maintain the proper flat characteristic and properly divide the load.

SECTION VIII CHAPTER XIII

DIRECT-CURRENT GENERATORS

PARALLEL OPERATION OF D. C. GENERATORS

1. Explain the inherent tendency of two shunt generators of equal capacity to equalize the load between them should one generator by some means become temporarily overloaded and the other underloaded.

2. Sketch two shunt generators with necessary switches and instruments arranged for operation in parallel. Assuming one to be carrying the load, explain in detail the procedure of starting the second generator and placing it in parallel with the first.

3. Assuming two shunt generators to be operating in parallel, how would the load be transferred to one and the other removed from the line?

4. Sketch two compound-wound generators suitably connected in parallel.

5. Explain why two compound-wound generators can not be operated in parallel without an equalizer.

6. Sketch two compound-wound generators together with all necessary instruments and switches arranged for operation in parallel. Assuming one machine to be carrying the load, explain in detail how the second machine would be started and placed in parallel with the first.

7. Assuming two compound generators to be operating in parallel, how would the load be transferred to one and the other removed from the line.

8. Under what conditions may two compound-wound generators of unequal capacity be operated in parallel?

9. If the resistance of the series fields of two compound-wound generators are not suitably proportioned for parallel operation, how may they be made so?

BOOSTERS

SERIES AND SHUNT BOOSTERS

The object of a booster is to boost the current on a certain circuit by interposing a variable e.m.f. in series with the main e.m.f. The necessity of this may be seen from a study of Fig. 401. Here a source, *A*, supplies a load, *C*, adjacent thereto. It is desired, however, to connect another load, *L*, a mile away on the same source. Evidently the voltage would fall in the feeder supplying the load and there would be a considerable difference in pressure between the points *C* and *L*. If, however, an auxiliary source, *B*, is connected in series between *A* and *L*,

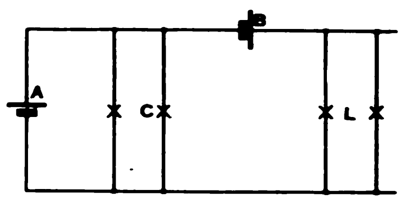


FIG. 401.

the voltage of the circuit can be raised sufficiently to overcome the loss due to the resistance in the feeder.

Series Booster

This principle was early applied for the purpose of equalizing the pressure on different sections of street railroads, located at widely different distances from the power house. Suppose a generator, *G*, Fig. 402, furnishes power for street railway loads situated at the points *A*, *B*, and *C*, at 1, 3 and 6 miles respectively from the station. If the generator is compounded for proper voltage at *A*, it would furnish too low a voltage at *C*. If compounded for the point *C*, the voltage would be too high at *A*. The sections of the system are therefore subdivided. *A* is furnished directly from the generator. Section *B* is supplied through a small series generator, *H*, in series with the feeder, *I*. If, now, the loss in the feeder is 50 volts, the booster will raise the voltage sufficiently to compensate for the loss in the

feeder and the load at B will receive the same voltage as the load at A. If the load C were connected through a feeder, L, of such length that 100 volts were lost, then a series generator K could be arranged to supply 100 volts, and thus compensate for the loss in the feeder. These auxiliary generators were simply series machines furnishing a practically straight line rising characteristic in which the increase in voltage was directly proportional to the current passing through their fields. As the loss in the feeder was likewise proportional to the same amount of current, the booster would compensate automatically for the

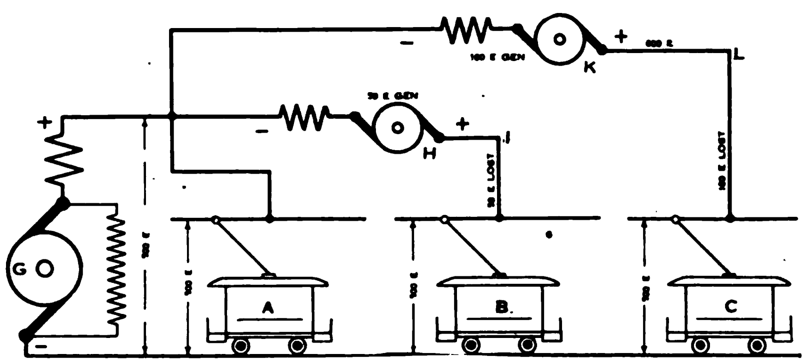


Fig. 402.—Principle of series booster illustrating boosting of the current in feeders of different lengths in proportion to the loss in the feeder so as to give uniform potential on all sections of the line.

feeder loss under all conditions of load and the points A, B and C would always receive the same voltage no matter how widely they were separated or how great the variation in load.

All boosters are driven at a constant speed by direct-connected shunt wound motors, connected across the main source of supply.

They may be hand controlled, automatic in their operation, self-exciting, or separately excited.

To operate lamps at 110 volts the minimum number of cells of battery required may be found by dividing 110 volts by the minimum voltage of one cell when it is discharged to the lowest value that is safe, 1.8 volts. Thus $\frac{110}{1.8} = 61$ cells, Fig. 403. Before the invention of boosters the only method of charging such a battery was to split it in half and connect the two halves

in multiple across a 110-volt generator, as in Fig. 404. Otherwise it would take at least 61 cells times 2.6 volts, per cell, or 159 volts to charge it. This plan was suggested by Planté. It is uneconomical because, when charging, if each series re

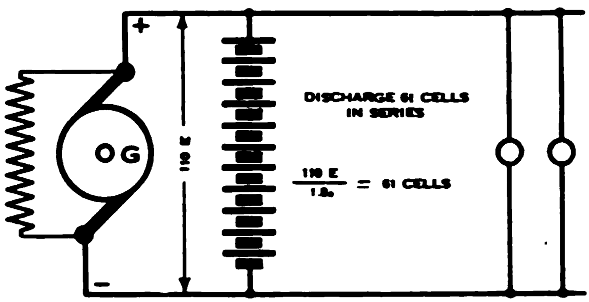


FIG. 403.—Storage batteries in multiple with shunt generator, showing minimum number of cells required at lowest point of discharge.

quired 50 amperes the two halves in parallel would require 100 amperes, while in discharging, the two sections being thrown in series, only 50 amperes could be drawn.

Non-Reversible Shunt Booster

By the use of the so-called shunt booster, this subdivision of the batteries is obviated and a much more economical arrange-

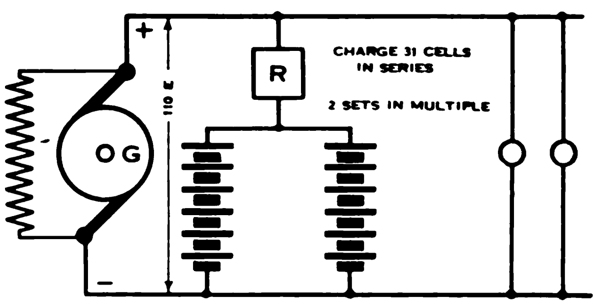


FIG. 404.—In the absence of booster to charge batteries it is necessary to subdivide the battery and place two sections in multiple.

ment is provided. The plan is shown in Fig. 405. Here a small direct-current generator, *B*, is connected in series with a battery of 61 cells, *C*, across the terminals of a 110-volt generator, *G*.

To charge this battery will require 61 times 2.6 volts per cell, or 159 volts. The generator will supply 110 volts. The difference, 49 volts, must be furnished by the booster. The field of this booster is connected in series with the rheostat *R* across the line. At the beginning of the charge when the battery's e.m.f.

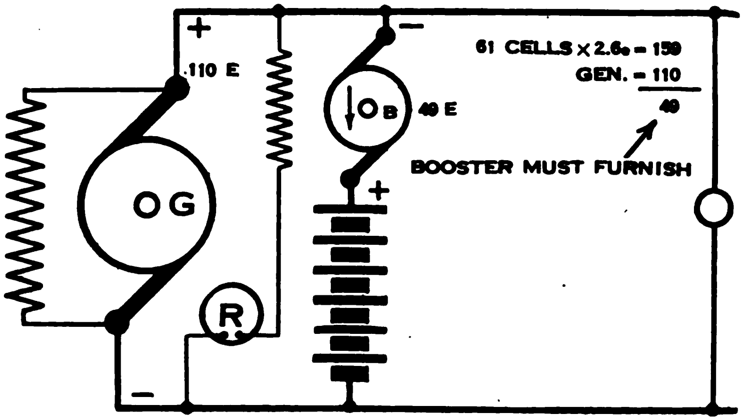


FIG. 405.—Non-reversible shunt booster used only to aid generator in charging battery. Booster is shut down and battery is thrown across the line when battery is charged.

is low, the booster need furnish but a few volts. As the charge progresses the voltage must be increased by altering the setting of the rheostat, *R*. Finally when the battery is fully charged, the booster's e.m.f. must be raised to 49 volts. If employed to help charge the battery only, it is known as a **non-reversible booster.** The term reversible or non-reversible does not apply to the direction of rotation, but to the direction of the e.m.f.

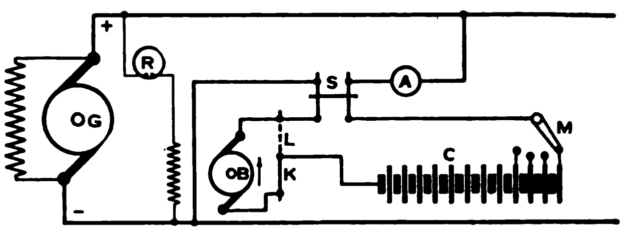


FIG. 406.—Non-reversible shunt booster and end cell switch for regulating the voltage of the battery to suit generator potential during discharge of the battery.

furnished by the booster. The voltage of a non-reversible booster is always in one direction. The voltage of a reversible booster may be altered by changing the direction of its field excitation, which will thereby reverse the polarity of the brushes. The wiring diagram for a non-reversible booster is shown in Fig. 406. Here the charging current passes through the ammeter *A*, the double pole switch *S*, the battery *C*, the single-pole double-throw knife switch *K*, booster *B*, to the negative side of the line. When the battery is charged the switch *K* is thrown into the dotted position, *L*. This cuts out the booster and ties the negative side of the battery directly to the negative line. As the working voltage of a battery is but two volts per cell, the delivered e.m.f. would now be 61 cells times 2 volts per cell equals 122 volts. This would be too high to operate in parallel with a 110 volt generator. The voltage is therefore reduced by an end cell switch, *M*, by means of which four or five cells may be cut out at the beginning of the discharge and gradually cut in again, to make up for the fall in battery potential as the discharge progresses. The blade of the switch, *M*, in passing from one contact to the next, must momentarily bridge two adjacent contacts. This is necessary to prevent opening the line circuit. Unless special precautions are taken, however, each cell in turn would be short-circuited during the transition of the blade from one contact to the next. To prevent this the end cell switch may be designed as shown in Fig. 407. The blade is divided into two sections, *A* and *B*, which are first insulated from each other and then connected by a resistor, *R*. The value of this resistor is such as to limit the current from the cell on closed circuit to the normal safe discharge amount. This prevents the cell from being short-circuited. When the blade finally moves to a contact segment between two cells, *A* and *B* both rest upon the same segment and the resistor *R* is itself short-circuited. Another type of end cell switch uses a single laminated arm sliding over copper contact blocks which have blocks of carbon placed

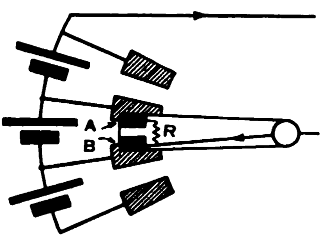


FIG. 407.—End cell switch showing arrangement for preventing short-circuiting of individual cells while switch lever is being moved from one segment to the next.

on each side. The resistance of these carbon blocks, as the end cells are short-circuited in the operation of the switch, limits the current to a safe value. Another type uses the e.m.f. of a separate cell to oppose the voltage of the short-circuited cell. This is called the counter e.m.f. type. Both types are usually motor driven in large installations.

Reversible Booster.

If the booster instead of being shut down after the battery is charged, is used reversibly to aid the battery in discharging as well as in charging, it may be made somewhat smaller or about three-fourths of the capacity of the non-reversible type. In this case, however, it must be run continuously as long as the plant operates. Fig. 408 illustrates a booster of this type. As the booster is to aid the battery in discharging as well as in charging, a somewhat fewer number of cells would be required. Fifty-six would be sufficient. 56 cells times 2.6 volts per cell equals 146 volts, necessary to charge the battery. If the generator furnishes 110 volts, then the booster must furnish on charge the difference or 36 volts. On discharge the battery's voltage will

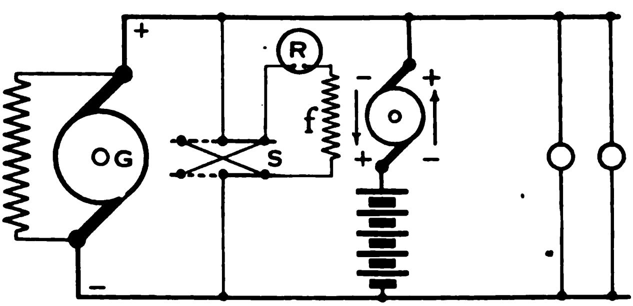


FIG. 408.—Reversible shunt booster used to aid generator in charging and also to aid battery when discharging to line.

fall to a minimum of 1.8 volts per cell times 56 cells, or 100 volts. If the lamps require 110 volts, the booster must now supply the discrepancy or 10 volts. To enable it to furnish a voltage in either direction, its field, *f*, is connected across the line through a reversing switch, *S*, and a field rheostat *R*. In the position shown, current from the line passes down through the field, *f*, regulated by the rheostat, *R*, until a maximum of 36 volts is supplied downward, aiding the generator in charging the battery.

When the battery is fully charged it will furnish 2 volts per cell times 56 cells or 112 volts. The booster voltage may now be reduced to zero by weakening the field and the 112 volts in the battery minus about 2 volts to overcome the resistance of the booster armature will deliver 110 volts in parallel with the generator to the load. As the discharge progresses and the battery voltage falls, it is necessary that the voltage of the booster be reversed. This is done by throwing the switch S into the dotted position, which will send a current upward through the field, f, the actual voltage required being adjusted by the setting of the rheostat R.

A peculiar feature of the reversible shunt booster is that it is driven by a motor of somewhat smaller kilowatt capacity than itself. This is because when charging, the current is limited to, say, 50 amperes, but the voltage may be as high as 36 volts. The power required is therefore $E \times I = P = 36 \times 50 = 1{,}800$ watts. When discharging, the current demand of the load may be high, say 100 amperes, while the voltage of discharge is low, not exceeding 10 volts. The power demand now will therefore be $E \times I = P = 10 \times 100 = 1{,}000$ watts. The maximum requirement of the booster is therefore 1,800 watts and the motor need only be large enough to supply this amount plus the losses. However, the field strength must be sufficient to enable the booster to generate 36 volts on charge and the armature winding must be of sufficient capacity to furnish 100 amperes on discharge. Therefore the kilowatt capacity of the booster must be $E \times I = P = 36 \times 100 = 3{,}600$ watts, while it may be driven by a motor of little more than half that capacity (1,800 watts plus the losses).

SECTION IX CHAPTER I

BOOSTERS

SERIES AND SHUNT BOOSTERS

1. Explain in detail the series booster used without storage batteries on railway systems for boosting the current on feeders. State how the booster is driven. Sketch its connections to line. To what extent does it compensate for voltage lost? How is the boosting adjusted? Through what range is the boosting uniform? What limits the ultimate amount of boosting?

2. Sketch connections for a shunt motor direct connected to series booster for railway circuits. Show all necessary series field shunts, circuit breakers, and switches. How is protection afforded against motoring of the booster in event of loss of power on the motor end?

3. Explain the object of a non-reversible shunt booster, the advantages gained from its use, and whether its regulation is accomplished automatically or by hand.

4. Sketch a non-reversible shunt booster suitably connected for charging storage battery in connection with main generator. Show all necessary instruments and switches.

5. Explain the object of a reversible shunt booster, the advantages gained from its use, and whether its regulation is accomplished automatically or by hand. Sketch.

6. On a storage battery plant operating at 220 volts, how many cells of battery would be required to maintain the pressure at all times provided a booster is not employed during discharge? How many cells would have to be cut out by hand regulation to keep the pressure normal?

7. What voltage will be necessary for a non-reversible shunt booster to fully charge a storage battery for operation on a 220-volt system? How many cells of battery will be required?

8. Explain the design of an "end-cell" switch.

BOOSTERS

AUTOMATIC BOOSTERS

The object of all automatic boosters is to maintain a constant load upon the generating plant while the connected load on the system varies widely. Power stations operate most efficiently at a constant load somewhere near their maximum capacity. The peak load usually lasts for only a few hours. If a generating plant is of sufficient capacity to supply this peak load, a good portion of it may be required to lie idle for 20 to 22 hours out of the 24. To smooth out the peak loads and make the demand upon the power station more nearly uniform, automatic boosters

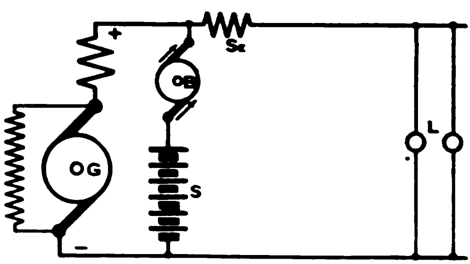


Fig. 409.—Original automatic booster with series field only. Armature is in series with battery across the line. Series field is in series with load current only.

were devised. The first automatic booster was devised by C. O. Mailloux, in 1890. The scheme is this: Assume a power station of 1,000 kilowatts capacity, carrying a load of 500 kilowatts. In order to load the plant to its maximum capacity the difference, or 500 kilowatts, is directed into a storage battery, where it is accumulated. Later in the day the load demand increases to 1,000 kilowatts. There is now no surplus to be put into the battery, but the entire output of the station is absorbed directly by the load. Still later the peak of the load comes on and the demand increases to 1,500 kilowatts. The storage battery now gives up the energy which it accumulated earlier in the day and supplies 500 kilowatts. The load upon the generating station is thus held constant at 1,000 kilowatts, while

the demand varies from 500 kilowatts to 1,500 kilowatts. The device which insures the input of 500 kilowatts into the battery during the period of light load and then causes the battery to neither charge nor discharge during medium load and then to discharge 500 kilowatts at heavy load, is the automatic booster.

The original scheme of Mailloux's automatic booster is shown in Fig. 409. Here the booster armature, B, is connected in series with the storage battery, S, across the generator, G. In series between the generator and the load, L, is the field winding of the booster, Se. The current in this field is the algebraic sum of the currents in the battery and the generator, which equal the current demand of the load. It is always in such a direction as to make the booster armature generate a voltage upward in the direction of the arrows, trying to make the battery discharge. When the load, L, is light, or when there is no load at all, the series winding Se is carrying no current, and consequently generating no flux. The booster therefore generates no voltage. The generator G furnishes a greater voltage than the counter e.m.f. of the battery and therefore charges the battery. As the load, L, now increases, the strength of the series field rises and the voltage of the booster B commences to build up in the direction of the arrows. This first tapers off the incoming current which was charging the battery, finally stopping it, and when the load L becomes sufficiently heavy, the booster's voltage rises enough to make the battery discharge in parallel with the generator to the load. This is called an automatic type of booster because when the load is light the booster permits the generator to charge the battery. When the load is increased the booster stops the generator from charging the battery. When the load becomes still heavier the booster automatically compels the battery to discharge and assist the generator.

The Differential Booster

A series winding or a shunt winding alone is not as effective in the regulation of any device as a combination of the two arranged to form a differential resultant. The differential booster is shown in Fig. 410. It was designed for use on railway and power circuits where the load varied widely and suddenly. At normal load the series field, Se, was designed to be of a strength exactly equal to the shunt field, Sh. As these two windings were connected in opposition no flux crossed the arma-

ture and the booster voltage was zero. Under these conditions the battery's voltage equaled the generator's voltage. The battery, therefore, floated on the line, neither charging nor dis-

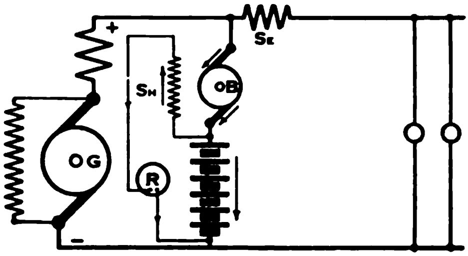


FIG. 410.—Differential booster aiding generator to charge the battery when load is light and series field is weak.

charging. If the connected load was 1,000 kilowatts, the generating plant would then furnish 1,000 kilowatts. If the connected load fell off to 500 kilowatts, the strength of the series field, *Se*, would fall to one-half value. The shunt winding, *Sh*, would now overpower the series winding and produce a flux across the armature in such a direction as to generate a voltage downward as indicated by the arrows, of say 20 volts. This, added to the generator's voltage, would be sufficient to charge the battery.

If the load increased to 1,500 kilowatts, the conditions would be as indicated in Fig. 411. The series field now becomes as

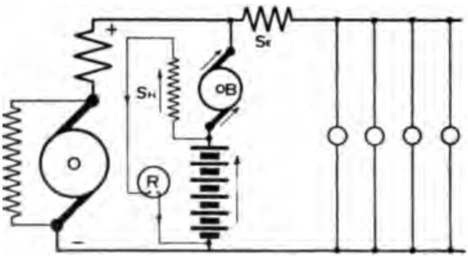


FIG. 411.—Differential booster aiding battery to discharge to line when series field is strong due to heavy load.

much stronger than the shunt field as the shunt field was stronger than the series field in Fig. 410. This would produce an equal flux in the opposite direction across the armature and the booster would generate a voltage upward of say 20 volts, as indicated by

the arrows. This, added to the battery's e.m.f., would be sufficient to make the battery discharge at the rate of 500 kilowatts, which, with the 1,000 kilowatts furnished by the generating plant, would supply the demand of 1,500 kilowatts.

Modified Differential Booster

If the battery voltage remained constant, the regulation as above outlined would be very satisfactory, but as the discharge progresses the battery's voltage falls. Thus, if the battery delivered 200 volts at the beginning of its discharge, this would fall toward the end of the discharge about 10% or to 180 volts. The battery plus the booster would then deliver only 200 instead of 220 volts. This may be partially compensated for by connecting the shunt field across the battery as shown. Then as the battery's voltage falls the shunt field excitation likewise falls, which is equivalent to strengthening the series field, and the booster's voltage rises. A fall of 10%, however, of battery voltage, or 20 volts, would only bring about a rise of booster voltage of 10%, or 2 volts, so that the compensation of this connection would be slight. To make the booster compensate for wide changes in battery voltages, a modified connection has been adopted, as shown in Fig. 412. Here the series field is divided into two

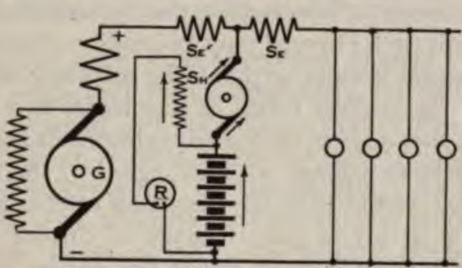


FIG. 412.—Modified differential booster with auxiliary series winding to automatically raise voltage of booster as discharge of battery progresses and thus compensate for loss of battery potential.

parts, *Se*, which varies with the load on the system, and *Se'*, which is normally constant, carrying the output of the generating plant. *Se* and *Se'* carry current in the same direction and both oppose the shunt field *Sh*. If *Se'* and *Sh* are constant in value normally, the regulation of the booster when so connected is

practically the same as before so long as the battery's voltage is constant. If, however, the voltage of the battery falls, the output of booster and battery combined falls. Assuming the demand of the connected load to remain unaltered, the generating plant must deliver whatever the booster and battery fail to deliver. Thus, as the output of the battery goes down, the output of the generating plant through the series field *Se'* goes up. This increase of current in *Se'* raises the discharging voltage of the booster. Therefore, any additional ampere output from the main generator is made to increase the booster's voltage through the increased effect of the winding *Se'* and thereby check any further increase in output from the generator. This proves very satisfactory in practice save that occasional adjustments of the shunt field rheostat *R* must be made to compensate for wide changes in battery voltage. It is, of course, necessary that the battery shall have a greater ampere-hour input than it is required to deliver. In other words, it must never be entirely discharged. This is controlled by the setting of the field rheostat *R*. If the resistance is cut out and the shunt field strengthened, the time of charge will be prolonged. If resistance is cut in and the shunt field weakened, the time of discharge will be prolonged. By a little experimenting, over a few days, the proper adjustment to insure that the battery shall always be kept sufficiently well charged may be readily effected.

The differential booster without the auxiliary series winding and some of the earliest forms of automatic boosters had the disadvantage that a given change of current in the series winding produced a definite voltage without regard to the fact that the battery voltage varied with the condition of charge of the battery. That is to say, a given change of current in the series field of a differential booster would not always automatically result in the desired rate of charge or discharge.

Another difficulty in this type of booster was the heavy current that had to be passed through the series winding. This required a conductor of massive cross-section and the machine had to have a frame of excessively large dimensions and weight per kilowatt of capacity. To overcome these difficulties there have been developed a number of automatic systems that regulate the booster's voltage through external means and insure the proper output from or input to the batteries regardless of

the condition of charge and consequent e.m.f. These latter systems have practically replaced the differential booster described above.

Hubbard Counter-E. M. F. Booster

The Hubbard counter-e.m.f. system is controlled by the Gould Storage Battery Company. It is shown diagrammatically in Fig. 413. The booster's armature, *B*, and storage battery are in series across the load. The field, *f*, of the booster is in series through a field rheostat *R*, with the armature of a small auxiliary exciter, *Ex*, the field of the latter, *f′*, being excited by the main

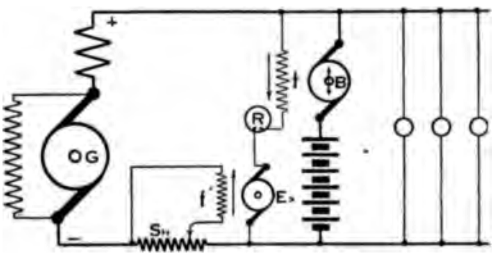


FIG. 413.—Hubbard counter e.m.f. type of booster with auxiliary exciter for automatically reversing polarity of booster field and thereby enabling booster to aid generator in charging battery or aid battery in discharging to line according to the requirements of the load.

generator current or a shunted portion thereof. The adjustments are so made that with normal load, the exciter, *Ex*, produces an e.m.f. equal and opposite to that of the line. Under these conditions no current flows through the booster field, *f*, and no e.m.f. is generated by the booster. As the battery's e.m.f. is equal and opposite to that of the generator, *G*, the battery simply floats on the line, neither charging nor discharging. If the load falls, then the current in *Sh* falls. The excitation of *f′* falls and the exciter's opposition to the line e.m.f. decreases. Current then flows downward through *f* and the booster generates a voltage downward and helps *G* to charge the battery. As the load becomes heavier, the current in *Sh* correspondingly increases, *f′* likewise increases and the exciter's voltage, *Ex*, becomes greater than that of the line. This reverses the current in *f* and likewise the booster's voltage. The booster now furnishes an e.m.f. in an upward direction which

aids the battery to discharge to the line. As the regulation is effected by varying the current in the field of an exciter, the arrangement becomes very effective, for a very slight change in f' produces a magnified change in the booster's voltage.

Entz Booster

The Entz system controlled by the Electric Storage Battery Company is illustrated in Fig. 414. This is specially designed for installations of large capacity. The entire station output passes through a solenoid, S, consisting of a few convolutions of heavy wire, and produces an electro-magnetic pull on a core attached to one end of a pivoted lever, L. At normal load the pull of the solenoid, S, is balanced by the opposing pull of a spring, M, so that the lever presses equally upon the stacks of

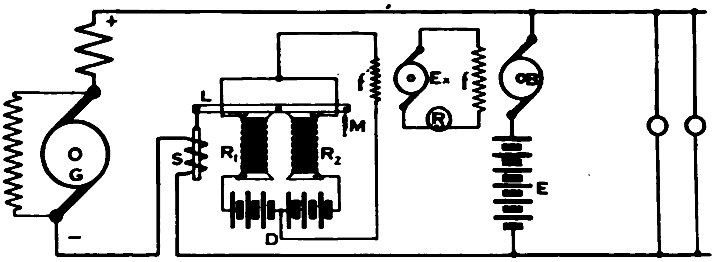


FIG. 414.—Electrical Circuits in the Entz Booster.

carbon plates, R_1 and R_2. These carbon stacks are connected in series at the top and supplied at the bottom with current from an auxiliary battery D. A connection is taken from the middle point of the battery and from the wire connecting the two carbon stacks in series at the top, to supply the field, f', of a small motor driven exciter, Ex. The armature of this exciter supplies current to the field, f, of the booster, B, through field rheostat R. If the auxiliary battery furnishes equal voltages from each section and the resistances R_1 and R_2 are equal, there will be no difference of potential between the terminals of f'. Consequently there will be no voltage generated by the exciter and none by the booster. This is the condition for normal load, when the main battery, E, furnishes an e.m.f. equal and opposite to that of the generator G, and floats upon the line, neither charging nor discharging. If the load falls, the solenoid S becomes weaker than the spring, M. The pressure on R_2 will be increased. This

likewise causes a reduction of the pressure on the stack R_1 which increases in resistance. The auxiliary battery will now send a current through f'. This will generate an e.m.f. in the exciter and energize the field of the booster. The connections are such that this will cause the booster's voltage to aid that of the main generator and thus charge the battery. If the load increases, the current through S will increase and the resistance of R_1 will fall, while that of R_2 will rise. This will cause a current to follow in the reverse direction through f', which in turn will reverse the polarity of f. Th's will cause the booster's voltage to aid the battery and br:ng about a discharge.

The arrangement of R_1 and R_2, together with the auxiliary battery and the exciter's field winding, f', is similar to the circuits of a Wheatstone Bridge, Fig. 415. The two halves of the

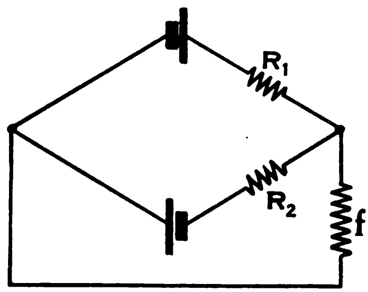


FIG. 415.—Theoretical arrangement of the circuits of Entz booster showing similarity to Wheatstone Bridge.

battery correspond to the ratio arms, and R_1 and R_2 to the rheostat and unknown resistance. The winding f' corresponds to the galvanometer circuit. The polarity of f' is affected by the same causes that make the galvanometer of a bridge circuit deflect one way or the other as the resistances of the bridge arms are varied.

If the installation is a small one the exciter, *Ex*, and the auxiliary battery, D, may be omitted. In fact the auxiliary battery is not absolutely necessary in any case for the main battery or a portion of it may be used directly. The object of the auxiliary battery is to avoid imposing unequal loads upon the individual cells of the main battery. If the exciter is omitted, the connections to f' are transferred directly to f, but this can be done only when the capacity of the booster and the field current to be handled are small.

SECTION IX — CHAPTER II

BOOSTERS

AUTOMATIC BOOSTERS

1. What is the object of an automatic booster?

2. Sketch all circuits in connection with an automatic booster having a series field in the line and an armature in series with the battery across the line. Explain its operation under all variations in load.

3. Sketch a differential booster with series and shunt field properly connected to generator, battery and load. Explain its operation under variations in load.

4. Sketch the modified differential booster with main series winding, auxiliary series winding and shunt winding, properly connected to generator battery and load. Explain its operation under all variations in load.

5. Sketch the Hubbard Counter e.m.f. type of booster, with storage battery, exciter and generator properly connected to load. Explain its operation under all variations in load.

6. Explain the Entz separately-excited booster with carbon stack for controlling direction and strength of exciter's field, together with battery and generator connected to load. Explain its operation under all variations in load.

SECTION X CHAPTER I

DIRECT-CURRENT MOTORS

MOTORS; PRINCIPLES; EARLY TYPES

An electric motor is a machine for converting electrical energy into mechanical energy. It is the converse of a generator. There is no essential difference in the electrical and mechanical design of generators and motors. They are as similar as an air engine compared with an air compressor. Obviously the same machine could be used both ways. That is, if compressed air is admitted to the cylinder of an automatic reciprocating engine it will run and develop mechanical energy. If, on the other hand, power is applied to forcibly rotate the fly wheel, the engine may be made to store air under pressure. Hence it becomes a generator of air pressure.

Another illustration of the similarity between a generator and a motor may be shown by a simple hand-operated automobile tire pump. When pressure is applied to the handle and the piston is forced downward, air is stored in the tire under pressure. The pump then becomes a generator of compressed air. If the valve leaks and the air returns into the pump it will force the piston upward. It then becomes an air motor. Electric motors and electric generators are as closely related to each other as are the two operations of the air pump just described.

Like the electric generator, the electric motor is a transformer of energy. In the generator, mechanical power is applied at the pulley and reappears at the brushes as electrical energy. In the electric motor, electrical energy is admitted at the brushes and the transformation proceeds in the reverse order, the energy reappearing as mechanical power at the pulley. The same transformer losses will be encountered when passing through the machine in either direction.

Historical

The first electric motor of which there is a record was known as Barlow's wheel, shown in Fig. 416. Here, a copper disc is mounted between the poles of a permanent magnet with provision for sending a current perpendicularly from circumference to axis of the disc, through a sliding mercury contact, *c*. The mag-

netic field of force produced by this current interacts with the permanent magnetic field, causes the disc to rotate. The sliding contact at the circumference corresponds to a commutator. The machine is almost identical in design with Faraday's disc which Michael Faraday designed five years later for the purpose of generating the first currents produced by means of electromagnetic induction. Faraday's disc was, in effect, a homopolar or acyclic generator.

The first motor depending upon attraction and repulsion of electro-magnets was devised by Joseph Henry in 1831. Following Oersted's discovery of the relation existing between magnetism and electrical currents in 1819, Sturgeon, in 1821, built some

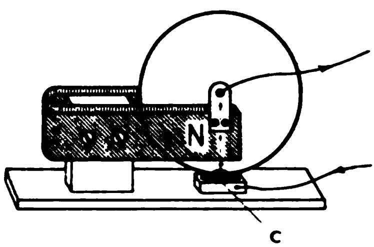


FIG. 416.—Barlow's wheel, the first electric motor.

powerful electro-magnets. At that time, however, it was supposed that electro-magnets could contain but one layer of wire The iron core was covered with a coating of wax within which a single layer of bare wire was embedded. To increase the number of turns the magnet was lengthened. This, of course, increased the magnetic reluctance of the core. It was thus found difficult to raise the magnetic flux very high. After considerable experimenting, Joseph Henry found that a magnet could be devised with several layers of insulated wire superimposed upon each other, thus permitting the saturation of the iron core to a high degree. With these powerful electro-magnets, Henry devised his first motor.

The first practical motor to develop any considerable power, and the most interesting from a scientific standpoint, was devised by Jacobi, in 1838. Aided by the Czar of Russia, he succeeded in building a motor consisting of a number of electro-magnetic spools, placed in a circle upon a wooden frame with a similar

set of magnets mounted upon a shaft, arranged to be attracted by the first so as to cause rotation. The movable set were first attracted until they moved into line with the stationary set. A commutator was provided to reverse the polarity of the moving set at this instant. The momentum carried the movable magnets past dead center with respect to the stationary magnets, and attraction ceasing, repulsion set in and the motion was continued toward the next set of stationary magnets. Jacobi used this motor successfully to propel a boat on the Neva at St. Petersburg. Power was derived from 138 cells of Grove battery. The motor developed about one horse power.

The first man to apply the electric motor to locomotion was Professor Page, of the Smithsonian Institution, of Washington. In 1850 he devised an electric motor consisting of two solenoids each alternately attracting a core of soft iron attached to opposite ends of a walking beam. When one core had completed its travel within its solenoid, current was switched out of this coil and into the other by means of a commutator; thus the reciprocating motion was maintained. This motion was transferred by a connecting rod to a crank which in turn operated to rotate the wheels of an ordinary flat car. On April 29, 1851, this car was run over the Washington and Baltimore Railroad as far as Bladensburg. It attained a speed of 20 miles an hour and employed a battery of 100 Grove cells to operate it. The motor developed about 16 horse power.

The most important early motor from a scientific standpoint was the one devised by Professor Pacinotti, of the University of Pisa, in 1861. This motor was not exhibited until the Vienna Exposition in 1873. It was conspicuous in that it had a slotted armature of the Gramme Ring type. It was at this exposition that Pacinotti pointed out the reversibility of the generator. He said that "whereas in the magneto-electric generator we apply mechanical power and take out electrical, in the electro-magnetic engine we apply electrical power and take out mechanical." Up to this time the majority of electric generators had been supplied with permanent magnets and were known as magneto-electric machines. Motors, however, operating solely by batteries, employed electro-magnets for producing their fields and were called "electro-magnetic engines." It was at the Vienna Exposition that the similarity of the two machines in principle

as well as in construction was pointed out. It was not, however, until some years later, about 1884, after the substitution of electro-magnets for permanent magnets in generators, that the reversibility of the dynamo-electric machine was fully realized.

Rotation of a Motor's Armature

The cause of rotation of a motor's armature may be understood by considering Fig. 417. Here a Gramme Ring winding is shown with current entering the armature by the upper brush and passing through the divided circuit both ways around the armature to the negative brush, where it leaves the armature. It will be observed that all of the conductors in the left-hand half of the armature carry current toward the observer, while the conductors on the right-hand side carry current away from the observer. Assuming the polarity of the field to be as indicated, the reac-

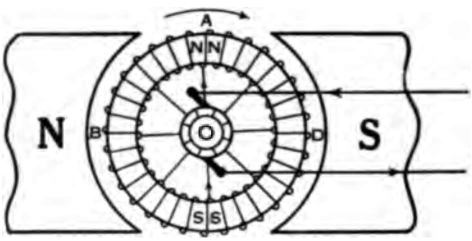


FIG. 417.—Illustration showing why the armature of a direct-current motor revolves.

tion of the armature current on the field flux will be as shown in Fig. 418. Here the conductor A on the armature carries current toward the observer. The flux rotates counter-clockwise around this conductor. A magnetic line of force from the field, in trying to pass this conductor, would be deflected downward as shown. On the other side of the armature the conductor B is carrying current away from the observer and hence the flux around it rotates clockwise. This would result in deflecting the field flux above it. A magnetic line of force acts like a stretched rubber band, tending to shorten itself, which will force the conductor A upward and the conductor B downward. In other words, the reaction of the magnetic field about A on the field flux causes A to roll itself upward out of this field, and B to roll itself downward in an effort to get out of the same field.

Due to commutation, the coils which pass from one side of the armature to the other, Fig. 417, have the current within them reversed as they pass under the brushes. This insures that the current in all of the conductors in the half of the armature winding, *A-B-C*, will continuously flow toward the observer while the

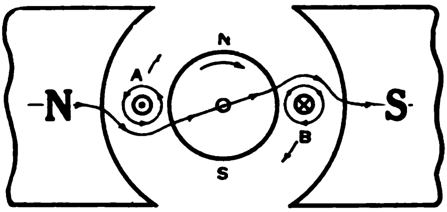


FIG. 418.—Illustration showing how conductors carrying current in a magnetic field tend to move.

current in all the conductors in the right hand side, *A-D-C*, will continuously flow away from the observer, which explains why the armature continues to revolve. Those on the left will therefore try to climb up out of the magnetic field while those on the right hand half are urged downward out of the field. Rotation of the armature is thus made continuous, because of the fixed position of the brushes.

Theoretically, every generator will operate as a motor provided it is supplied with the same kind of current as that which it

FIG. 419.—Direction of currents, resulting polarity and direction of rotation of a series generator.

produces as a generator. Likewise every electric motor, if supplied with mechanical power, will produce current as a generator. This is literally true in practice with the exception of a few small toy motors which are so designed that they will not operate as self-exciting generators.

If current is passed through the field and armature of a series generator, as in Fig. 419, the magnetic polarity of the field will be shown at *N*. One pole is omitted to simplify the diagram. The current in passing through the armature will tend to produce polarity as indicated. According to Lenz's Law, "the reaction of the induced currents tend to oppose the motion which pro-

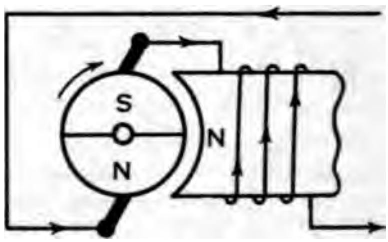


FIG. 420.—Direction of currents, resulting polarity and direction of rotation of series motor.

duces them," and if the armature is forcibly rotated in the direction shown by the arrow, it is evident that the magneto-motive-force of the armature, in its reaction on the magnetic field, will oppose this direction of rotation. If current is sent through this machine so as to operate it as a motor, the direction of current and polarity being the same as before, the same magneto-

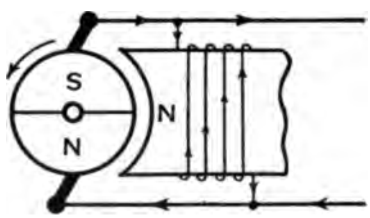


FIG. 421.—Direction of current, resulting polarity and direction of rotation of shunt generator.

motive-force in the armature and polarity of the field will be established in Fig. 420. If now the mechanical force of rotation is withdrawn and the armature is free to move in obedience to the magnetic forces, it will rotate in the opposite direction to that in which it was formerly driven. Hence **a series generator, arranged to run as a motor, will run backwards.**

Fig. 421 illustrates the magnetic conditions in a shunt wound generator. Current passing out over the upper wire and back in the lower wire will establish the same polarity in the field and magneto-motive-force in the armature as was indicated in the series generator. The forcible rotation of the armature in the direction of the arrow will oppose the magnetic reaction between the armature and the field. Fig. 422 represents the conditions in the same machine run as a motor. The current is supposed to enter by the lower wire and come out by the upper wire as in Fig. 421. The removal of the source of current from within to without the machine, however, results in reversing the current in the field winding, establishing a south pole in the motor where in the generator there was a north pole. The current passes through the armature, however, in the same direc-

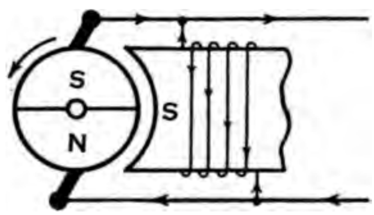


FIG. 422.—Direction of current, resulting polarity and direction of rotation of shunt motor.

tion as before. The reversal of the field current without reversing the direction of the current in the armature reverses the tendency of this armature to run backward. **Thus a shunt generator connected to run as a motor runs forward or in the same direction as it ran as a generator.**

If a series generator tends to run backward, and a shunt generator tends to run forward, as a motor, it might be supposed that a compound generator would not run at all as a motor. If the series and shunt field windings exerted equal magneto-motive-forces this would be literally true. Practically, however, the shunt is much stronger than the series winding. Hence a compound generator runs in the same direction as a motor as that in which it ran as a generator. But the flux from the series winding would oppose the shunt field flux and tend to weaken the interaction between the armature and field, for the two windings

would operate differentially with respect to each other. This opposing combination of series and shunt field windings is rarely used for motor operation.

Consider the relation existing between generators and motors in Fig. 423. If a machine is to be operated as a motor and the polarity of the field and magneto-motive-force of the armature are maintained unchanged, then the directions of rotation would be opposite, as shown by the arrows. Under these conditions, the **brush position must not be changed** and what constitutes a forward angle of lead, L, in the machine as a generator, amounts

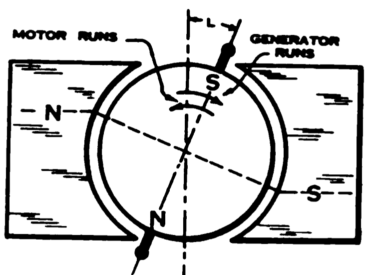


FIG. 423.—Illustration showing relative direction of rotation of motor and generator provided armature and field polarities are maintained the same in both cases.

to a backward angle of lead when the same machine runs as a motor.

If, instead of running a machine in opposite directions the connections are altered so as to make it revolve in the **same** direction as a motor, as that in which it ran as a generator, the conditions will be as shown in Fig. 424. Here the field will be distorted in the direction N'-S', when operating as a generator. The magneto-motive-force of the armature, practically perpendicular thereto, will be N'-S'. The angle of lead for the brushes will be L'. To enable this machine to run in the same direction as a motor, it would be necessary to reverse the polarity of either armature or field. Assuming that the connections to the armature are reversed, the magneto-motive-force will be reversed. The field distortion will now be in the opposite direction to that in a generator, namely, N-S. The brushes must be placed so as to

bring the armature magneto-motive-force practically perpendicular thereto or on the line, *S-N*. To do so will necessitate giving them a backward lead, *L*, equal to the forward lead which the machine had as a generator when running in the same direction.

The effect of reversing the lead, which is given to the brushes

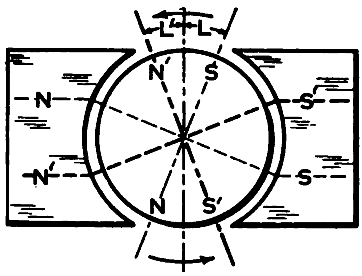


FIG. 424.—Relative polarity of armature and field in generator and motor and brush position when machine rotates in the same direction in both cases.

in either a generator or a motor, is illustrated in Fig. 425. Assuming the brushes to be on the line, *B-D*, and the field distortion as shown, the armature reaction would tend to weaken the field. The demagnetizing belt causing this result would be

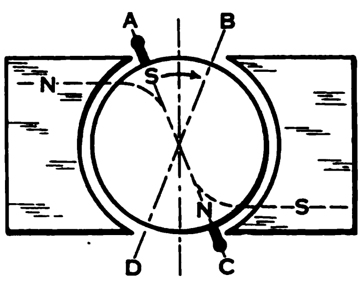


FIG. 425.—Backward lead of brushes on generator assisting field magnetism instead of opposing it.

embraced within the double angle of lead, *A-B* and *D-C*. If, now, the brushes were shifted on to the line *A-C*, giving them a backward lead equal to the forward lead, the **demagnetizing belt** above referred to will be converted into a **magnetizing belt** and the magneto-motive-force of this belt instead of opposing

the main field actually supplements it. It would be theoretically possible to cause the armature to not only supplement, but actually induce, its own field magnetism so that a machine could be constructed without any field magnetizing coils at all, by giving the brushes a sufficient backward lead. Practically, destructive sparking at the commutator would make the application of this principle prohibitive.

SECTION X CHAPTER I

DIRECT-CURRENT MOTORS

MOTORS; PRINCIPLES; EARLY TYPES

1. Define an electric motor. Wherein do motors and generators differ?

2. Why does the armature of a direct current motor revolve?

3. (*a*) If a series generator is set to run as a motor, in what direction will it revolve?

(*b*) If a shunt generator is set to run as a motor, in what direction will it revolve?

(*c*) If a compound generator is set to run as a motor, in what direction will it revolve?

4. If a generator is set to run as a motor, in the reverse direction, must the brush lead be changed? Why? Sketch.

5. If a generator is set to run as a motor in the same direction, must the brush lead be changed? Why? Sketch.

6. If the brushes on a generator are given a backward lead, or the brushes on a motor be given a forward lead, what will be the effect upon the field magnetism?

DIRECT-CURRENT MOTORS

THE REGULATION OF D. C. MOTORS

The armature conductors in a motor cut the magnetic lines of force of the field in which they rotate in the same way as in a generator. In Fig. 418 the conductor, *A*, moves up through the field because it carries a current toward the observer, but as this conductor cuts the lines of force of the field there is generated therein an e.m.f., the direction of which is away from the observer, or in the opposite direction to that in which the current is actually flowing. This is in accordance with Lenz's Law, for if the motion of the conductor is due to a current therein, the induced e.m.f. must necessarily be in opposition thereto.

Regulation of Shunt Motor

A shunt motor is essentially a constant speed machine; that is, it tends to operate at practically a constant speed under all variations in load. The same causes which contribute to **constancy of voltage** in a generator likewise contribute to **constancy of speed** in that same machine when operating as a motor. These causes are, first, a constant field strength, and second, a low armature resistance.

Consider a shunt motor operating under a moderate load. Line *A-C*, Fig. 426, represents an impressed e.m.f. of 100 volts. The e.m.f. generated in the armature will be directly proportional to the speed. It will be assumed that when it runs at a speed of 1,000 r.p.m., its counter e.m.f. will be 99 volts, represented by the line *C-B*. The actual current in the armature will be determined by the effective e.m.f., which is the difference between *C-B* and *A-C*, or *A-B*. This will be one volt. If the armature has a resistance of 0.1 of an ohm, then the armature current, *Ia*, will be determined by the formula,

$$Ia = \frac{Ef}{Ra} = \frac{1}{0.1} = 10 \text{ amperes.}$$

Where Ia = armature current.

Ef = effective e.m.f.

Ra = armature resistance.

It will be assumed that this current of 10 amperes will carry the load imposed upon the motor at the above mentioned speed of 1,000 r.p.m.

Next assume that the load increases on the motor. If it were operating a lathe, this increase in load could be brought about by setting the tool deeper into the work so as to take a heavier cut, and therefore calling for more power. The first result of the increased load would be to react on the armature, and cause it to slow down. As it does so, the counter e.m.f. falls in direct proportion to the reduction in speed. By the time the speed has fallen, however, about 1%, to 990 r.p.m., the effective e.m.f. would have increased from one volt to two, as in Fig. 427. Applying the above formula it will be seen that the current now flowing will be $Ia = \frac{2}{0.1}$ or 20 amperes. With double current in the armature it will be able to develop double torque, and consequently do approximately twice the work.

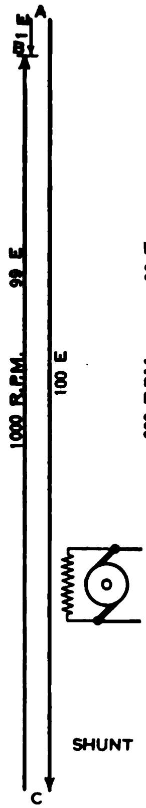


FIG. 426. FIG. 427.

The effective e.m.f. for a given load is determined as before stated, by the resistance of the armature. If the resistance is very low, the effective e.m.f. is, in the first place, low. Therefore when the load increases, it will only be necessary that the **speed** be **reduced a very small per cent** in order to bring about **a very large per cent increase in effective e.m.f.** and therefore in current and torque. In the case under discussion a reduction in speed of approximately 1% results in an increase in torque of about 100%. Thus, under changing conditions in load, a very slight alteration in speed brings about a very large change in armature current.

Regulation of Series Motor

A series motor varies widely in speed under variations in load, for two reasons. First, the motor has a variable field, and second,

the armature and field combined have a comparatively high resistance. Assume a series motor carrying a given load at a speed of 1,400 r.p.m. Line *A-C*, Fig. 428, represents the impressed e.m.f., 100 volts, and *C-B* the counter e.m.f., 90 volts. The effective e.m.f. is now *A-B*, or 10 volts. If the armature and field in series have a resistance of 1 ohm, the current flowing through the motor will be

$$I = \frac{10}{1} \text{ or 10 amperes.}$$

If, now, the load increases on the armature, it reacts as in the case of any motor under the increase and begins to slow down. If the load has doubled, the armature must decrease in speed sufficiently to get the current required to produce double torque. If the field strength were constant, as in a shunt motor, the armature current would have to double in order to produce double torque, but as the field and armature are in series, an increase of current in the motor raises the strength of both. Therefore, to bring about double torque the current in both need increase only about 40%. This may be illustrated as follows: If, in a shunt motor, the strength of the field is taken as 10 and the strength of the armature is taken as 10, then the torque may be regarded as the product of these two factors, 10 times 10 equals 100. If the load doubles, the strength of the field remains constant as before at 10. The current must now double in the armature, giving it a value of 20. Then 10 times 20 equals 200, which will be a measure of the torque required for double load. Consider the corresponding illustration for a series motor. Assuming the strength of the field to be 10, and that of the armature to be 10, the torque will be proportional to the product of these two, 10 times 10 which equals 100.

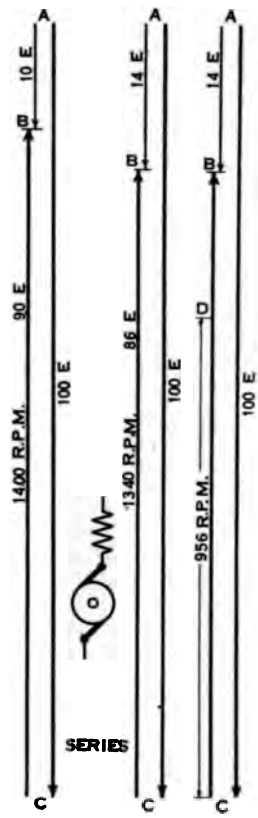


FIG. 428. FIG. 429. FIG. 430.

If, now, the load increases so as to call for double torque, the field does not remain constant but increases. It will, therefore, take a field strength of only 14.1 multiplied by an armature value of 14.1 to equal the required torque of 200.

If the field had a constant strength it would only be necessary, in order to enable the armature to get 40% more current, that the speed should fall enough to reduce the counter e.m.f. from 90 volts in Fig. 428, to 86 volts, as shown in Fig. 429. This would allow the effective e.m.f. to increase from 10 volts to 14 volts. Applying Ohms Law, the armature and field would now get,

$$I = \frac{Effec.\ E}{R} = \frac{14}{1} \text{ or 14 amperes.}$$

The speed would fall in direct proportion with the counter e.m.f., thus $90 : 86 :: 1{,}400 : X$. From which $X = 1{,}340$ r.p.m.

But as this 14 amperes comes through the series field on its way to the armature, the magnetic flux (assuming the cores are not saturated) is increased 40%, say from 1,000,000 lines to 1,400,000 lines. With this increased flux the counter e.m.f. would also rise and thereby prevent the input of the required 14 amperes unless a still further reduction in speed is brought about. As the motor must have 14 amperes in order to develop the required torque, the speed continues to fall. The actual extent to which it will drop may be determined in the following way. If the speed were 1,340 r.p.m., to produce the required 86 volts counter e.m.f., with 1,000,000 lines, then with 1,400,000 lines, the required speed would be found by the inverse proportion, 1,400,000 lines : 1,000,000 lines :: 1,340 r.p.m. : X. From which X = 956 r.p.m. as *CD*, Fig. 430. The speed has now fallen from 1,400 r.p.m. to 956 r.p.m., under an increase in load calling for double torque. This drop in speed is about 32% as compared to a drop of 1% in a shunt motor under a corresponding demand. With a constant impressed voltage the counter e. m. f. is always proportional to the product of the flux per pole and the speed. In the shunt motor, the flux being constant, the counter is therefore proportional to the speed alone, but in the series motor the flux and speed will vary in nearly inverse ratio. Hence line *C B*, Fig. 430, can no longer represent both speed and counter, but should truly represent the counter e. m. f. of 86 volts, because if

the flux has increased 40% and the speed has decreased 40% the counter should remain the same as in Fig. 429. The final speed

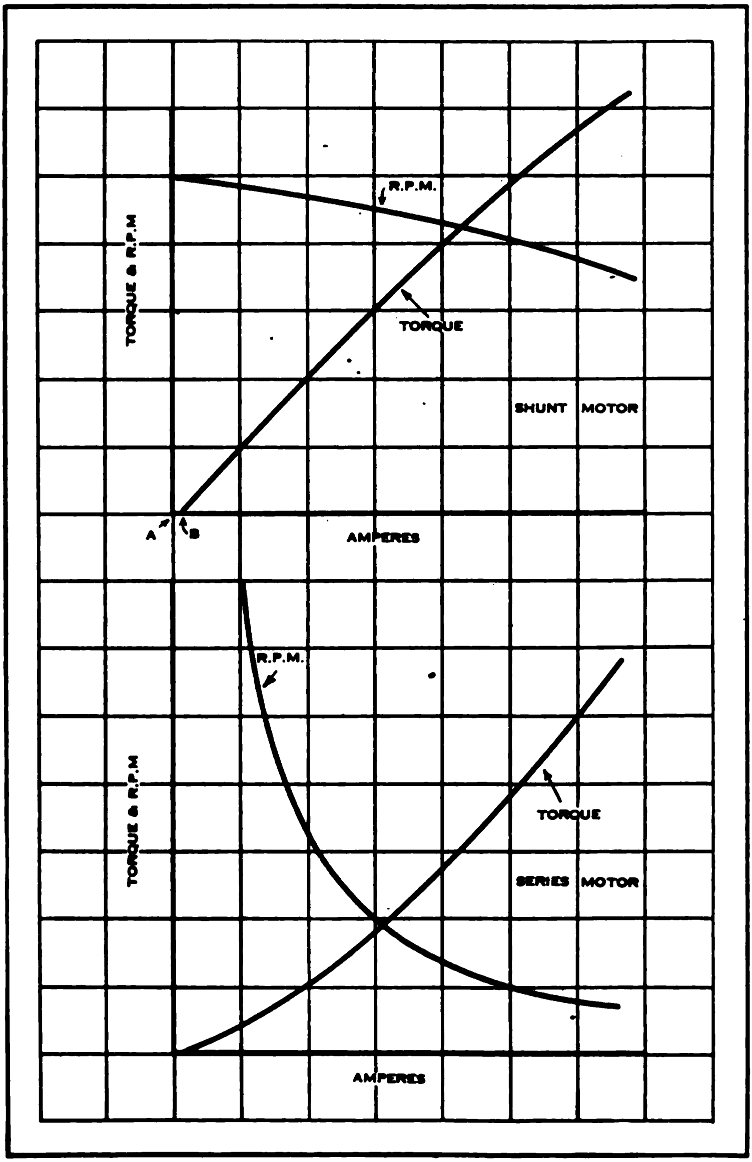


FIG. 431.—Speed and torque curves of shunt motor.
FIG. 432.—Speed and torque curves of series motor.

of 956 r. p. m. can perhaps be shown to another scale as in line $C\ D$, Fig. 430.

The foregoing discussion illustrates the principle involved. Both examples are purposely exaggerated. The shunt motor actually varies somewhat more in speed and the series motor somewhat less under the stated load demands.

The characteristics of a shunt motor are illustrated in Fig. 431. Here revolutions per minute, as ordinates, are plotted against amperes input to the armature as abscissas. The speed falls slightly. It will be observed that this curve is almost identical in appearance with the voltage curve representing the external characteristic of a shunt generator. The torque curve for this machine is a straight line. The small armature input between A and B represents the current necessary to rotate the armature without any load, after which the torque rises directly in proportion to the armature current.

The corresponding characteristics for a series machine are shown in Fig. 432. Here the speed is seen to be infinitely high at no load. This is literally the case. A series motor should never be started without a load, because it tends to run at a speed which will destroy it. This infinitely high speed occurs for the following reason: Without load the armature theoretically requires no current. It will, therefore, rise in speed in an effort to generate a counter e.m.f. equal to that impressed, so as to reduce the current intake to zero, but when it is taking no current there is likewise no current in the field winding which is in series with the armature, and therefore no flux across the armature. It will be **necessary,** therefore, **for the armature to run at an infinitely high speed,** in a **field of no strength** in order **to generate the required counter e.m.f.** Practically the armature takes a little current to overcome the losses. Therefore there is a very weak field, but in that field the armature must run at a dangerously high speed to generate a counter e.m.f. which approaches the impressed. As the load increases, the speed drops rapidly. As the speed falls the torque rises. The series motor has an advantage over other types, in the large torque which it will develop for a given increase in current. Doubling the current in the armature would double the current in the field. Neglecting saturation, this would cause quadrupled torque between armature and field. Thus, the torque of such a machine would

vary as the square of the current. Practically, on account of saturation, the torque only varies a little faster than the current. Nevertheless, at very low speeds, the series motor develops the largest torque of any direct-current motor.

Speed Variations

It will be well to here consider the relative speed variations of the four possible types of direct-current motors under variations in load. The **series motor varies most widely in speed.** It develops a **very large torque.** Its speed varies inversely with the torque, although not always in exact ratio.

It will be remembered that the series generator delivered a variable potential on a variable load when run at a constant speed. Similarly the series motor will run at a variable speed on a variable load when supplied with a constant potential.

A **compound motor varies considerably in speed,** though not so much as a series motor yet more than a shunt motor. The **torque is less** than in a series machine but more than in a shunt machine.

A **shunt motor** is **nearly constant in speed** under changes in load and develops a **torque somewhat less** than a compound motor.

A shunt generator maintains approximately a constant potential under variations in load when run at a constant speed.

A shunt motor maintains approximately a constant speed under variations in load when supplied with a constant potential.

A **differential compound motor,** when operated on a constant potential circuit, has the **least torque** of any D. C. machine, and it may have a **constant speed or** it may be made to **rise in speed** instead of falling, with an increase in load.

A compound generator, if flat compounded, maintains nearly a constant potential under variations in load when driven at a constant speed. Now if the connections are not altered, this machine, set to run as a motor, becomes differentially compound, and as such maintains nearly a constant speed under variations in load if supplied with a constant potential. If a compound generator is overcompounded 10% for a rise in potential under increasing load, that same machine, when run as a motor, would become a differentially compound machine, without any alteration of connections, and when so operated would rise in speed approximately 10% from no load to full load.

Compound motors with their fields in addition are frequently used for the operation of elevators. In such a case it is desirable to have a larger torque to start the heavy load than is obtainable from a shunt machine, and yet have a more uniform speed than is possible with the series machine. The compound motor furnishes the requisite torque to start. As soon as the elevator reaches its normal speed, the series winding is automatically cut out, after which the motor runs with the constant speed characteristic of a shunt machine.

There are very few instances where a differentially compound motor is desirable. The opposition of the field windings may practically destroy the field flux and prevent the development of any torque. If, however, such a machine is started with proper precautions and without load, it may be employed in a few special cases, where a very close approximation to an absolutely constant speed is desirable. One instance is in the driving of 500-cycle alternators for wireless operation on shipboard. By using an over compounded generator to supply the differential motor, this motor is made to hold a sufficiently constant speed and therefore deliver a constant frequency of 500 cycles from the alternator under all variations in load. This is quite desirable in wireless transmission.

For most stationary machinery in industrial plants, the ordinary shunt motor maintains a sufficiently close approximation to constant speed for all practical requirements.

Armature reaction in a motor weakens the field and helps maintain the speed more nearly constant under variations in load. Therefore the armature ampere-turns may be made greater in a motor than in a generator of the same size and regulation.

SECTION X CHAPTER II

DIRECT CURRENT MOTORS

THE REGULATION OF D. C. MOTORS

1. Why does a shunt motor maintain a practically constant speed under all variations in load? What are the factors which determine this constancy of speed?

2. Why does a series motor vary in speed and torque under variations in load? To what extent do these factors vary? How do these factors vary with respect to each other?

3. Sketch a speed curve and a torque curve for a shunt motor. Analyze and explain.

4. Sketch a speed curve and a torque curve for a series motor. Analyze and explain.

5. (*a*) What will be the effect of entirely removing the load from a shunt motor? Why?

(*b*) What will be the effect of entirely removing the load from a series motor? Why?

6. (*a*) What will be the effect of loading a shunt motor to a standstill? Why?

(*b*) What will be the effect of loading a series motor to a standstill? Why?

7. Explain the effect upon the speed and torque of a compound motor in which the series field aids the shunt, when the load is altered.

8. Explain the effect upon the speed and torque of a compound motor in which the series field opposes the shunt, when the load is altered.

DIRECT-CURRENT MOTORS

MOTOR STARTING BOXES

As the resistance of a motor armature is low, and as the counter e.m.f. does not exist until the motor is running, it is necessary that an external resistance should be inserted in series with the armature to limit the current until the armature has had time to generate its counter e.m.f.

Assume a motor designed for 220 volts and requiring 55 amperes in its armature at full load. The armature resistance is 0.2 of an ohm. The field of a shunt motor is always wound to stand the full line voltage and may be thrown directly across the line, where it will take only the current for which it is designed. If the armature is likewise thrown across the line, however, the current which it will be forced to take at the start will be

$$\frac{E}{R} = I \qquad \frac{220}{0.2} = 1{,}100 \text{ amperes.}$$

Obviously this would burn up an armature whose normal current was 55 amperes. In order to limit the current in the armature circuit to the safe value of 55 amperes, the required resistance would be

$$\frac{E}{I} = R \qquad \frac{220}{55} = 4 \text{ ohms.}$$

The armature itself possesses 0.2 of an ohm. The difference, then, $4.0 - 0.2 = 3.8$ ohms which must be inserted in series with the armature when starting the motor. If 55 amperes flows through this 3.8 ohms, Fig. 433, the pressure would be reduced 209 volts. This would leave 11 volts, which is the effective e.m.f. necessary to overcome the armature's resistance of 0.2 ohm. When the armature has reached its full speed, it will generate 209 volts counter e.m.f., which will replace the 3.8 ohms in the resistance box. At half speed, the armature will be generating one-half of this counter e.m.f. or 104 volts. There-

fore, when the motor reaches one-half speed it will be safe to reduce the resistance in the box to the following amount:

$$\textit{Impressed } E - \textit{Counter } E = \textit{Effective } E.$$

$$\frac{\textit{Effective } E}{I} = \textit{Resistance of circuit.}$$

$$220 - 104 = 116 \qquad \frac{116}{55} = 2.1 \textit{ ohms.}$$

Deducting the armature's resistance from this value, 2.1 ohms resistance of circuit minus 0.2 ohm resistance of armature gives 1.9 ohms resistance in box. By the time the motor has accelerated to full speed it would be safe to reduce the resistance in box from 1.9 ohms to zero, when the counter e.m.f. would entirely replace the resistance. The resistance should be cut out *gradually*, giving the motor time to accelerate for each notch on the box.

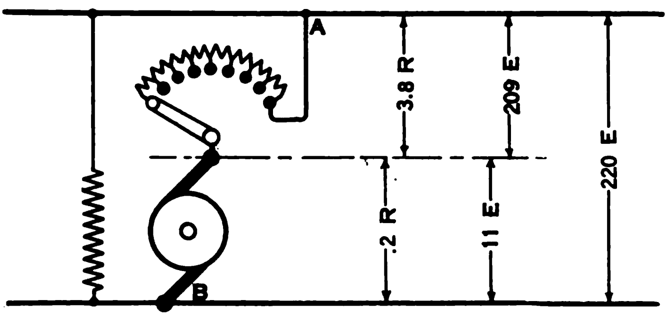


FIG. 433.

If the motor is small the starting resistance may be cut out rapidly, but the larger the motor and the greater the inertia, the more time must be allowed in which to cut out the resistance. If the starting current is increased beyond the safe full load value, the armature is strained mechanically and electrically.

A voltmeter placed across the wires *A-B*, Fig. 433, would measure the line voltage. To ascertain the counter e.m.f. in any particular case it is necessary to know, in addition to the line voltage, the current in the armature and the resistance of the armature. The counter e.m.f. may then be calculated as follows: The impressed e.m.f. minus the product of the armature current and the armature resistance equals the counter e.m.f.

Thus, if the motor were running at full speed and full load, taking say 55 amperes of current, the counter e.m.f. would be 220 − (55 × 0.2) = 209 volts. If now the load was reduced so that the armature took but 25 amperes, the speed would rise slightly and the counter e.m.f. would be 220 − (25 × 0.2) = 215 volts.

Starting boxes are designed so that a series of resistance coils in the armature circuit of a motor may be cut out successively as illustrated in Fig. 434. Here current entering from the line *A* passes to the lever *L* of the starting box. As soon as this lever is moved to the contact *B*, current flows via the wire *C* and a small electro-magnet, *E*, through the shunt field, *Sh*, to the negative side of the line, *D*. At the same time the current passes through

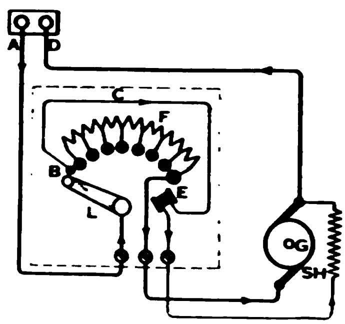


FIG. 434.—Internal connections of starting box for small D. C. motor.

a series of tinned iron wire coils, *F*, through the armature, *G*, and thence out by the common wire *D* to the other side of the circuit. As the lever is moved across the box, one section of the starting resistance after another is cut out of the armature circuit until finally the lever rests upon the poles of the magnet, where it is retained by its magnetic attraction against the tension of a spiral spring, which tends to hold it in an "off" position. When the lever is in the full "on" position the current for the shunt field must flow back through the armature starting resistance, *F*, to reach the wire *C*. If the resistance is low and the field current small, the product of the two causes a small drop in potential for this field current. It therefore does not appreciably diminish the actual current reaching the field winding. On large motors the field current is not led through the starting resist-

ance when running, but in small motors the above type of box is generally used.

In all types of motor starting boxes, a double-pole knife switch is required to break both wires leading to the motor, unless the starting box itself is designed to accomplish this result.

The above-mentioned box is designed to automatically sever the connections between the motor and the line in case the source of supply fails from any cause. The magnet *E* is therefore known as a **no-voltage release magnet.** This implies that, should the line voltage fail, the magnet *E* will be de-energized, with the result that the spring will restore the lever *L* to the "off" position. If the lever remained in the "on" position and the voltage was restored to the line, the armature would be

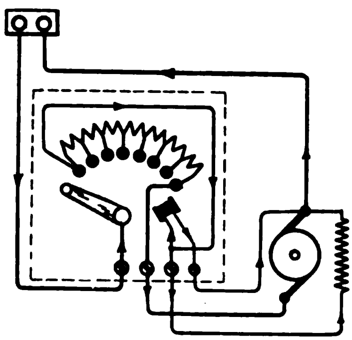


FIG. 435.—Internal connections for starting box for shunt motor showing no-voltage release magnet in shunt with the field.

subjected to full pressure without the protection of the starting resistance *F*.

The no-voltage release magnet may be connected in any one of three different positions.

First, in series with the entire motor. Because of the wide variations of armature current under changes in load, this is not a reliable place in which to connect it.

Second, in series with the shunt field. Here it brings about a drop of approximately 10% of line voltage and therefore of field current. It is commonly so connected for the operation of small motors as in Fig. 434. Where motors are to be adjusted in speed by means of field control, however, it is not satisfactory

in this position as a weakening of the field may reduce the strength of the magnet so as to make its operation uncertain.

Third, the no-voltage release magnet may be connected in shunt with the entire machine as in Fig. 435. This is considered the best position for a no-voltage release. It is then dependent for its operation solely upon the line potential and is not affected by a variation of either the field strength or the armature current. It is usually so connected for the control of all large motors.

To stop a motor, the lever on the box should not be forced into the "off" position, but the main switch should be opened. This will leave the field circuit in shunt with the armature. The momentum of the armature causes its counter e.m.f. to

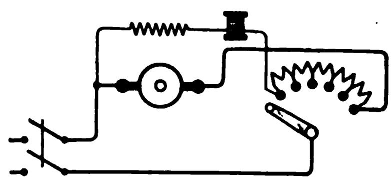


FIG. 436.—Correct wiring connections for starting box for small shunt motor with no-voltage release magnet in series with shunt field.

immediately establish a current through the no-voltage release magnet and the shunt field, in the same direction as the current which a moment before passed through this circuit from the line. As the armature slows down, its potential falls, and with it the current in this circuit until finally the no-voltage magnet becomes so weak that the lever is released. This will usually be some seconds after the main switch is pulled, and after the current in the shunt field has fallen so low that there is no danger that the opening of this circuit will cause an e.m.f. of self-induction which might injure the insulation.

Small motors do not require starting boxes, their armatures being light and their inertia small, they spring quickly into motion when thrown across the line, and establish the requisite counter e.m.f. to reduce the current to a safe value before the initial inrush of current has time to burn them out. Motors of one-fourth horse power and upward usually require starting boxes. With a larger motor, the inertia of the armature is such

that it takes considerable time for it to accelerate to full speed and unless a limiting resistance is inserted to start, it will blow the fuses which protect it, or the armature will burn out. For small motors, boxes wired as shown in Fig. 436 are employed. Here the closing of the main switch does **not** energize the field

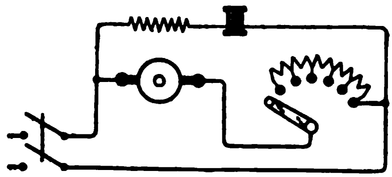


FIG. 437.—Correct wiring connections for large shunt motor energizing field and no voltage release magnet as soon as main switch is closed.

of the motor. As soon as the lever touches the first point on the box, however, the field and no-voltage release magnet are energized and the armature is connected in series with the starting resistance.

Fig. 437 shows the method of wiring starting boxes for large motors. Here, on account of the self-induction of the field winding and the hysteresis of the field frame, it is considered desirable to have the field winding energized as soon as the main switch is closed.

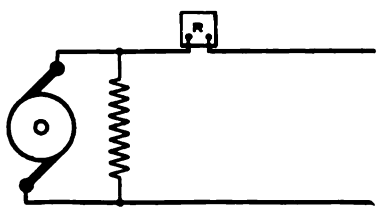


FIG. 438.—Starting box in wrong position in series with entire motor.

It is important that the starting resistance shall never be placed in series with the whole motor as in Fig. 438, but in series with the armature only, as in Fig. 439. If it is wired as in Fig. 438, the current which is allowed to pass the box will go through the armature instead of going through the field, for the armature's low resistance acts as a virtual short circuit on the field. As the resistance is cut out of the box the drop in potential across

the armature rises. It may get high enough to divert sufficient current through the shunt field to finally cause the armature to start. If it starts at all, it will start with a rush, when the resistance is almost wholly cut out of the box. With such connections the motor may take many times its normal current while starting.

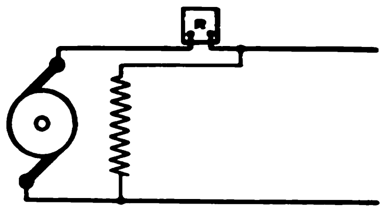


FIG. 439.—Starting box in right position in series with armature only.

The proper connections are shown in Fig. 439. Here the field which is wound for line voltage is connected behind the starting resistance, so as to insure full strength. When current is admitted through the starting box to the armature, it finds a fully established field on which it may exert torque. The connections in the boxes, Figs. 436 and 437, correspond to the right arrangement shown in Fig. 439. It is a very easy matter, however, to get the main wires between the motor and the box crossed, with the result that the wrong connections of Fig. 438 are established. This condition for the small box is shown in Fig. 440, and for the large box in Fig. 441. In the small box, the wire which should lead from the line to the lever of the box and the wire which should lead from the armature to the last point on the box are crossed.

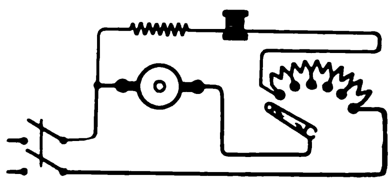


FIG. 440.—Incorrect connections for starting box for small motor showing armature in shunt with field circuit as soon as lever touches first point on the box. This corresponds to the wrong connections shown in Fig. 438.

Now, when the main switch is closed the field is energized. While that was desirable in the box for large motors, it is not necessary in this type of box, for small motors. The instant

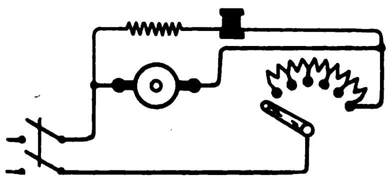


Fig. 441.—Incorrect connections for starting box for large motor showing armature in shunt with field circuit as soon as lever touches first point on box, corresponding to the wrong position in Fig. 438.

the lever is moved to the first point on the box, the armature and field are thrown in parallel and the starting resistance in series with both. Should the motor fail to start on the first or second point, it usually indicates that the connections are wrong and an inspection should be made at once. It is not safe to continue to move the arm across the box in the hope that the motor may start. Fig. 441 shows this reversal of connections in a large box. Here, the wire from the armature, which should go to the lever of the box, and the wire from the line, which should go to the last point on the box, are crossed with the result pictured. The conditions in starting are precisely the same as in Fig. 440. Closing the main switch, however, does not energize the field. As soon as the lever touches the first contact on the box, the armature and field, which have previously been connected in parallel, are thrown in series with the starting resistance with the result as before outlined.

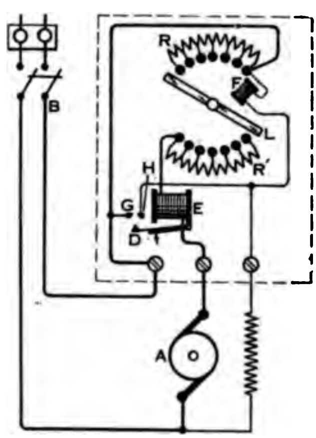


Fig. 442.—Wiring connections for starting box with no voltage release and overload cut out for operating shunt motor.

To protect motors from excessive current when running, overload cutouts are provided. A common form consists of an electro-magnet, *E*, Fig. 442, in series with the armature of the motor. When current is admitted, by closing the main switch, the field is energized directly from the line, *B*, in series with the low-voltage release magnet, *F*. As the lever *L* is rotated, current is admitted through the starting resistance, *R-R'*, thence through the overload magnet, *E*, and armature, *A*, to the other side of the line. If the current exceeds the safe carrying capacity of the motor armature, the magnet *E* attracts its armature, *D*, and closes contacts *G-H*. This short-circuits the terminals of the no-voltage release magnet, *F*, which promptly releases the lever, *L*, and the spring throws the arm into the "off" position, thus disconnecting the motor. While this is satisfactory for overloads while the motor is running, it is not approved as an exclusive protection against excessive currents, because it is not operative in starting, as the lever *L* may be held by the hand on some intermediate point of the box, and even though *E* should operate, it would not succeed in opening the line because the lever was forcibly retained in position. To use this type of protection, therefore, a fusible cutout must also be provided which will protect the motor during starting. Large motors are usually provided with electro-magnetic circuit breakers, connected in the main line, so that the circuit will be automatically opened if the current exceeds the predetermined safe amount, no matter whether the motor is just being started or is in full operation.

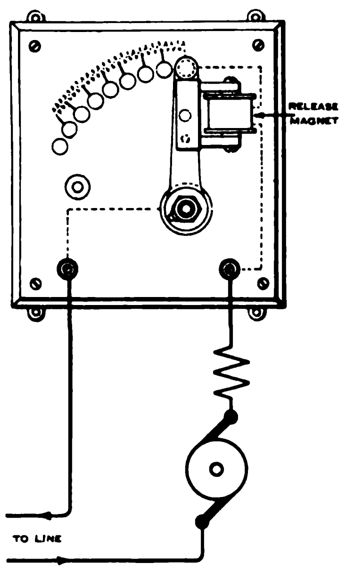


FIG. 443.—Wiring connections for starting box for series motors.

Starting boxes for series motors have the no-voltage release magnet, a starting resistance, the series field and armature, all wired in series as shown in Fig. 443.

Compound motors are wired in the same manner as shunt motors, with the simple addition of the series field in the armature circuit.

Reversing Switches

To reverse the direction of rotation of a motor it is not sufficient to reverse the current in the entire machine. If current passes through a motor as shown in Fig. 444, establishing the polarity of field and magneto-motive-force in the armature, as shown, the reaction of the armature current on the field poles will cause the armature to rotate in the direction of the arrow. If, now, the current is reversed at the terminals of the machine as shown in Fig. 445, the polarity of the field is reversed and likewise the magneto-motive-force of the armature. The resulting torque between the two is not altered, and the armature revolves in the same direction as before. If, however, the current in the field is reversed, as shown in Fig. 446, while the current in the armature remains the same, as in Fig. 444, the direction of the torque between the two will reverse and the

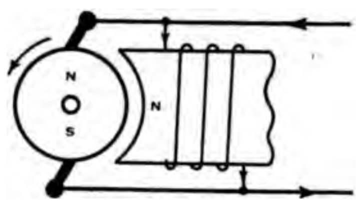


FIG. 444.—Polarity of motor and resulting direction of rotation.

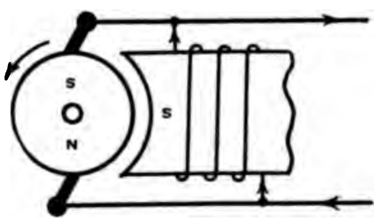


FIG. 445.—Reversal of current in motor reverses polarity of both armature and field and does not affect resulting direction of rotation.

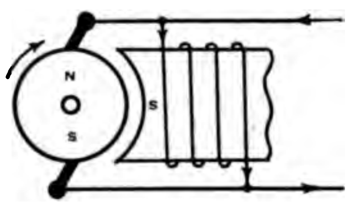


FIG. 446.—Reversal of polarity in armature or field results in reversing direction of rotation.

armature will run in the opposite direction, as the arrow indicates.

A simple reversing switch for a series motor is shown in Fig. 447. Here the lever, *L*, holds the circuit open on the motor. If moved to the left the plates on the lever connect with two stationary plates and through wires to the field of the motor and

current passes upward through the field, *F*, and then down through the armature *A* and out to the line. If, now, the lever is moved to the right, current will be directed down through the field by the cross connections and thence through the armature as before. This will reverse the direction of the torque between the two.

Fig. 448 illustrates the wiring for a reversing switch in connection with a shunt motor and an ordinary starting box. This requires a three-pole double-throw knife switch. In the position shown in the figure, closing the main switch, *S*, will admit current to the lever *L*. When the lever is moved to the right, current will pass through the no-voltage release magnet, *R*, shunt field, *Sh*, and thence via blade 1, of the switch, to the negative side of the line. At the same time the current is admitted through the starting resistance and via blade 3 of the switch and wire, *A*, to the armature of the motor, thence via blade 2 to the negative side of the line. To reverse the motor the three-pole switch is opened. This breaks the line and immediately releases the lever, *L*, which automatically moves to the "off" position. When the switch is thrown into the downward position, shown by the dotted lines, the motor is connected to operate in the reverse direction when started by the lever, *L*. When *L* is again moved to the right, current passes down through the shunt field as before, but that passing through the starting resistance passes through blade 3′, and down through the motor armature, thence up through blade 2′, and out through the negative side of the line. Blade 1 is simply employed to provide a circuit for the field in both positions of the switch, while blades 2 and 3 are employed to reverse the armature current.

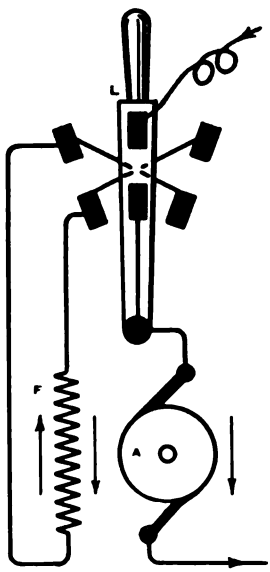


Fig. 447.—Reversing switch for small series motor.

It is not customary to use a separate reversing switch and a standard starting box, as shown in Fig. 448, on a shunt motor. It is more common to employ a reversing controller as shown

in Fig. 449. Here the closing of the main switch energizes the shunt field and no-voltage release magnet in series therewith. In use with large motors, this magnet would be in shunt with the field. This controller reverses the current in the armature and obviates the necessity of opening the field circuit when reversing the motor. As the field is wound for the line voltage it can be left permanently across the line while the armature circuit is opened. If, however, the field circuit were reversed, to reverse the direction of rotation, the armature could not be left across the line because, upon the disappearance of its counter e.m.f. its resistance would be so low as to short circuit the line. Hence the controller is much simpler if designed to reverse the armature current as shown, instead of the field current. When the controller handle is moved to the left, current is admitted through the starting resistance, through the overload cutout magnet and armature. If moved to the right, the same starting resistance is employed but the current is led through cross connections so as to reverse its direction in the armature. This type of overload cutout could evidently not be used to short-circuit the no-voltage release magnet if the latter were wound for line voltage and connected across the line, as it would then short-circuit the line.

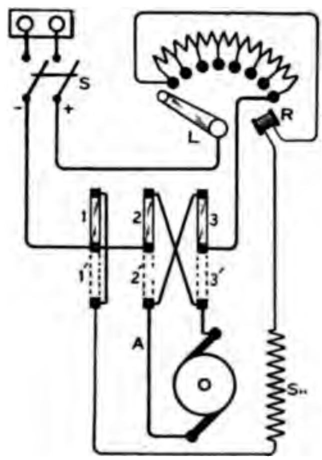


FIG. 448.—Reversing switch for use with ordinary starting box for reversing shunt motors.

A motor should never be reversed suddenly, because at the moment of reversal the counter e.m.f. of the armature is added to the impressed e.m.f. from the line. Let Fig. 450 represent a motor with an impressed e.m.f., E, of 220 volts and a counter e.m.f., C, at full load, of 209 volts. The effective e.m.f., Ef, would then be 11 volts. In an armature with 0.2 ohm resistance, this would produce 55 amperes. If, now, this armature has its connections suddenly reversed, it will be evident that the impressed e.m.f. and the counter e.m.f. are momentarily thrown in series with each other instead of in opposition, Fig. 451

The effective e.m.f. then, instead of being their difference, which is 11 volts, would be their sum, which is 429 volts. This would produce a current of over 2,000 amperes momentarily which

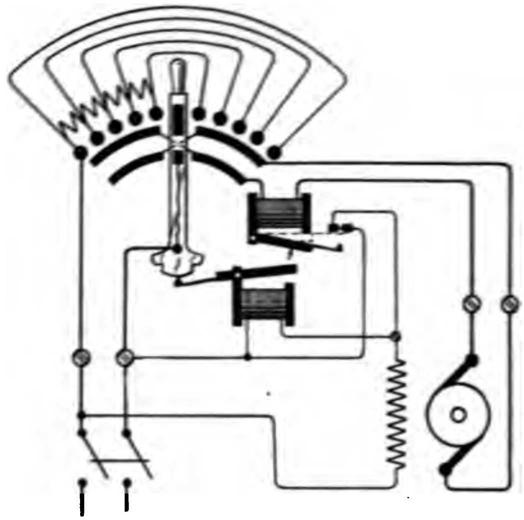


FIG. 449.—Combined starting box and reversing switch for shunt motors.

might be sufficient to destroy the armature. Therefore, when a motor is reversed, time should be allowed for the armature to slow down, stop, reverse, and start in the opposite direction

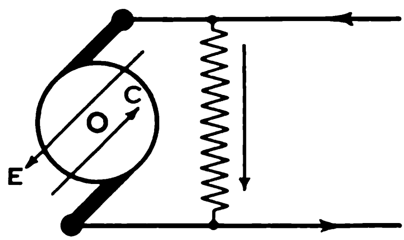


FIG. 450.—Relative directions of impressed e.m.f. and counter e.m.f. in shunt motor.

before the lever is moved beyond the first reversing point. The starting resistance will then, to a large measure, protect the armature against the excessive current due to the momentary

addition of the counter e.m.f., and the impressed. As the motor slows down, the counter e.m.f. falls with it. When it stops, the counter e.m.f. disappears entirely. When it reverses

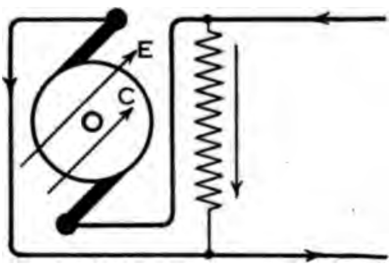


FIG. 451.—Reversal of current in armature momentarily adds impressed e.m.f. to counter e.m.f.

the counter e.m.f. builds up again in the opposite direction. Emphasis should be laid upon the fact, however, that the reversing must be accomplished even more gradually than the initial starting of the motor.

SECTION X CHAPTER III

DIRECT CURRENT MOTORS

MOTOR STARTING BOXES

1. Why must a starting box be employed with a motor?

2. If the armature resistance of a motor is 0.5 of an ohm and a current of 10 amperes is passing under a line pressure of 110 volts, what are the values of the impressed e.m.f., the counter e.m.f., and the effective e.m.f. respectively?

3. A 220-volt, 30-ampere shunt motor having an armature resistance of 0.4 ohm and a field resistance of 110 ohms, requires a starting box. How much resistance must the box contain?

4. What is the object of the no-voltage-release magnet?

5. In what three positions may the no-voltage-release magnet be connected? What are the relative advantages and disadvantages of these different locations?

6. When should the main switch be made to energize the field winding of a shunt motor and when is it not necessary?

7. Sketch a starting box for a large shunt motor with main switch and no-voltage-release magnet in shunt with the line, properly wired to shunt motor.

8. Sketch a starting box for a small shunt motor with main switch and no-voltage-release magnet in series with shunt field properly wired to motor.

9. What will be the effect of wiring the starting resistance in series with the entire shunt motor instead of in series with the armature?

10. Sketch starting box for a large shunt motor improperly wired as indicated.

11. Sketch starting box for small shunt motor improperly wired as indicated.

12. Sketch starting box with no-voltage-release properly wired to series motor.

13. Explain the operation of a simple overload cutout magnet attached to starting box for a small motor in which the no-voltage-release magnet is in series with the shunt field.

14. What circuits must be established in order to reverse the direction of rotation of a shunt motor?

15. Sketch reversing switch for a small series motor.

16. Sketch a reversing switch and separate starting box for a small shunt motor.

17. Sketch a reversing controller with no-voltage-release magnet and overload cutout for a medium size shunt motor.

18. What is the danger of suddenly reversing the current in the armature of any motor while operating at full speed?

DIRECT-CURRENT MOTORS

MOTORS; SPEED; TORQUE; EFFICIENCIES

The output of any motor is proportional to the product of its speed and torque.

The **torque** of a motor is its **rotating effort,** its **turning moment,** its **tendency to revolve,** and is measured in pound-feet. That is, the product of the radius of its pulley, in feet, and the pull at its circumference in pounds is equal to its torque.

The **speed** of a motor is measured in **revolutions per minute.** From this, the circumferential velocity under which the torque is manifested may be calculated. Consider a motor having a pulley $\frac{1}{6}$ foot in radius, or 4 inches in diameter, Fig. 452, to which there is attached a rope which supports a weight of 33 pounds. The torque due to the current in the armature is found by the formula, $T = r \times$ *lbs.*, where r equals radius of pulley in feet and lbs. equals weight sustained at circumference of pulley. Applying the formula, $\frac{1}{6} \times 33 = 5.5$ pound-feet torque. Twice the radius equals diameter of pulley, $\frac{1}{6} \times 2 = \frac{1}{3}$ foot diameter which multiplied by 3.1416 gives the circumference, in this case approximately one foot. If the torque is sufficient to cause the armature to revolve it is evident that the weight will be raised one foot per revolution which at 1,000 revolutions per minute will equal a rise of 1,000 feet per minute. Thirty-three pounds rising 1,000 feet in a minute is a rate of doing work equivalent to 33,000 foot-pounds per minute, or one horse power. The expression for the horse power of a motor, therefore, is:

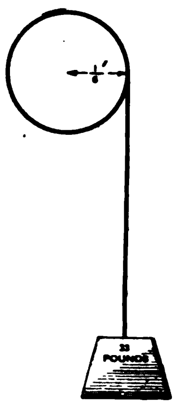


FIG. 452.

$$\frac{2\pi\, rn \text{ lbs.}}{33{,}000} = \text{horse power.}$$

Where π = 3.1416
r = radius of pulley in feet.
n = number of revolutions per minute.
lbs. = weight lifted.

Combining, $r \times lbs. = torque$, the above formula may be simplified as follows:

$$\frac{2\pi\, rn \text{ lbs.}}{33{,}000} = \text{horse power.}$$

From which

$$\frac{6.28\, n\, T}{33{,}000} = \frac{n\, T}{5{,}252} = \text{horse power.}$$

Where T = torque in pound-feet.
$2\pi = 6.28$.
n = revolutions per minute.

This expression is equally true for any motor, gas, steam or electric. In an electric motor the **speed** is directly proportional to the **counter e.m.f.**, while the **torque** is directly proportional to the **current** in the armature. The **horse power which** the motor develops is therefore directly proportional to **the product** of the **incoming current** and the **counter e.m.f., strange as this may** seem, for these two factors are in opposition to each other. The horse power which a motor **absorbs** is proportional to the **product** of the **impressed e.m.f.** and this **same incoming current.**

The rating of a motor in horse power is inconvenient. The 1914 Standardization Rules of the American Institute of Electrical Engineers recommend that motors as well as generators shall be rated in kilowatts, but until the industry becomes accustomed to this rating, it is suggested that motors be rated both in horse power and kilowatts. As a convenient and closely approximate equivalent, it is useful to remember that the horse power rating of a motor, may for all practical purposes, be taken as 4/3 of the kilowatt rating.

Motor Applications

The work required of motors may be such as to call for:

1. Constant torque and constant speed.
2. Constant torque and a variable speed.
3. Variable torque and a constant speed.
4. Variable torque and variable speed.

First. That kind of work requiring a constant torque and a constant speed. Under this head will come any load which does not alter. This includes small fans, ceiling fans, exhaust fans and rotary pumps. Series motors operating from constant potential circuits are best adapted for this class of work because of their ability to adjust themselves in speed to the requirements

of the load. A little consideration of the subject will show that shunt motors would not be able to do this as satisfactorily. Consider a ceiling fan with the blades set very flat. If driven by a shunt motor, the speed of which is limited, the consequent displacement of the air would be small. On the other hand if the blades were set at a very great angle, the reaction on the driving motor might slow it down far below its normal speed and greatly overload it. With a series motor, however, on such a fan, with the blades set quite flat as, in the first case, the speed would rise, driving the fan fast enough to displace considerable air, even though there was little pitch to the blades. On the other hand if the blades were set at a very great angle, the motor would be able to adapt itself to a much lower speed, developing a rapidly increasing torque when so doing. It would thus be able to move considerable air, and yet as the torque increases and the speed falls it could do so without being materially overloaded. This ability of a series motor to adjust itself to the requirements of a load over a wide range in speed makes it better adapted to a constant load of the above character. The actual speed to which a series motor automatically adjusts itself under these conditions is reached in this way. At the start, the initial rush of current develops in the motor a maximum torque. At the same time the resistance of the load, such as a fan, is practically zero. The large torque readily overcomes this minimum resistance of load and the motor rapidly accelerates. As it rises in speed the resistance of the load increases, but this increase in speed is accompanied by a rise in counter e.m.f. and a diminution of current and torque. The **rising resistance** of the **load** and the **falling torque** of the **motor** proceed toward a certain point where the resistance of the load exactly balances the torque of the motor at some particular speed. The motor naturally gravitates toward that speed and when this exact balance is attained, any further alteration in speed ceases, for the torque of the motor and the resistance of the load are then in equilibrium.

Second. A constant torque and a varying speed. There is practically no class of work today that calls for a variable speed without also requiring a varying torque. When electric power was first available, some cranes and hoists were so operated when the only power to be had was that derived from motors operated on constant current circuits. While this application

is not found now, the performance of a motor under these conditions is interesting. Series motors, on constant current circuits, all take the same current, regardless of their size. A one horse power motor and a 5 horse power motor in series would both take the same 10 amperes if that was the current maintained in the circuit. The difference, however, would be that the drop in potential across the one-horse motor would be approximately 100 volts and that across the five-horse motor, nearly 500 volts. While shunt motors at constant potential take a varying current in proportion to the horse power developed, series motors at constant current would take varying potentials in proportion to the horse power developed. Under the above conditions, to start such a series motor, a short circuit around it would have to be opened, which would loop the motor in the circuit. No starting box is necessary, for the motor cannot burn out, as the current is limited to the 10 amperes in the line. If the load is within the range of the motor's torque, the motor starts. If not, the motor remains stationary. If it starts it rises in speed, but its counter e.m.f., instead of reducing the current in the motor, raises the drop in potential across its terminals. If the drop in potential were 100 volts at 100 r.p.m., it would be 300 volts at 300 r.p.m. and so on. It would continue to rise in speed until the resistance of the load balanced its torque at a particular speed. Under these conditions the torque being fixed, the horse power developed by the motor varies directly with the speed. To regulate such a motor, mechanical governors were provided, operated by a pair of fly balls, which served to move a commutating switch on the machine and cut out sections of the field winding as the speed rose and thereby controlled the torque. This arrangement is not used now, as series motors at a constant potential supply the requirements for this class of work.

Third. Variable torque and constant speed. This class of work includes almost all stationary machinery such as lathes, drill presses, milling machines, shapers, boring mills, planers, etc. Here it is necessary that the machine shall operate at practically the same speed at all loads. For this work shunt motors operated at constant potential are best adapted. The slight variations in speed under variations in load are not objectionable.

Where a greater torque is required to start the load than can readily be furnished by a shunt motor, compound motors are

employed. As before stated, these motors are specially adapted for elevator work. Here the moderate starting torque of the shunt motor is considerably supplemented by the series winding. When the motor has started its load and begins to gain in speed, the series winding is automatically disconnected, after which the machine operates with the constant speed characteristics of a shunt motor.

Fourth. Work calling for a variable torque and variable speed. This includes electric vehicles of all kinds, automobiles, street cars, electric locomotives, also cranes and hoists. Series motors operated at constant potential are best adapted for this work, because their torque varies inversely with the speed and they are able to adapt themselves over a wide range of speed to the requirements of the load.

Should a shunt motor be applied to a street car and geared to drive that car at a given speed on a level, when the car approached a heavy grade, it would be obliged to drive the car up the grade at the same speed as on the level. This would call for an abnormal increase in power far beyond the capacity of an ordinary street car equipment. If a series motor operated at constant potential is applied to the car, it will carry the car on a level at a certain speed and when the car approaches a grade the motor will readily slow down under the increased load, taking more current and simultaneously increasing the field strength as well as that of the armature. The torque rises faster than the current because of the variable field and the motor is able to carry the car up the grade at a greatly reduced speed but without materially increasing the power required.

Motor Efficiency

The power absorbed by a motor may be expressed as follows:

$$P.W. = Em \times Im.$$

The electrical horse-power absorbed by a motor may be expressed:

$$E.H.P. = \frac{Em \times Im}{746}.$$

The power which a motor actually converts or generates in its armature is:

$$P.w. = Ea \times Ia.$$

The Electrical Efficiency is $\frac{P.w.}{P.W.}$

Where *E. H. P.* = Electrical horse power.
Em. = E.m.f. of mains applied.
Im = Current drawn from mains by motor.
P.W. = Power absorbed by motor.
P.w. = Power utilized or generated by motor armature.
Ea = Counter e.m.f. generated by armature.
Ia = Current absorbed by armature.

As the impressed e.m.f. is a factor of the power applied, and the counter e.m.f. is a factor of the power delivered by the motor, it will be seen that the ratio of the counter e.m.f. to the impressed e.m.f. is a measure of the electrical efficiency of the motor.

The following table shows a comparison of the various efficiencies in generators and motors. The difference is that the progress through the machine as a motor is in the reverse order to that in a generator. In both cases, however, the commercial efficiency which is the ratio between the delivered power and the absorbed power, is the same.

$$\text{For Generators} = \frac{\textit{Generated}}{\textit{Absorbed}} \times \frac{\textit{Delivered}}{\textit{Generated}} = \frac{\textit{Delivered}}{\textit{Absorbed}}.$$

$$\textit{Gross} \times \textit{Electrical} = \textit{Commercial}.$$

$$\text{For Motors} = \frac{\textit{Output at pulley}}{\textit{Gen. in armature}} \times \frac{\textit{Gen. in armature}}{\textit{Absorbed}} = \frac{\textit{Output at pulley}}{\textit{Absorbed}}.$$

Stray power losses	*Copper losses*
Hysteresis	I^2R in armature
Eddy currents	I^2R in field
Friction	

Jacobi's Law of Maximum Work

Jacobi's law of maximum work is an expression to show under what conditions a motor will develop its maximum horse power. It states that **a motor does work at a maximum rate when its counter e.m.f. is reduced to one-half the impressed.**

If a motor is running without load at a maximum speed, its counter e.m.f. is practically equal to the impressed. It therefore develops practically no torque. Although its speed is a maximum, its torque, which is a factor of its power, being zero, the power developed by the motor is zero. If, on the other hand, the motor is loaded to a standstill, it will then receive from the line a maximum current in its armature. This will develop a maximum torque, but as its speed, the other factor of its power, is zero, the motor again develops no power. It is obvious that

somewhere between maximum torque and zero speed and maximum speed and zero torque, at both of which extremities there is zero power, the motor will be able to develop a maximum power. Jacobi states where this point will be. His law is, in fact, a special application of the more general law that "the product of two quantities whose sum is fixed, is a maximum when these quantities are equal." As an illustration of this general law, take any two numbers whose sum is 100 and consider the various products that are obtainable.

Thus:

$$90 \times 10 = 900$$
$$80 \times 20 = 1600$$
$$70 \times 30 = 2100$$
$$60 \times 40 = 2400$$
$$50 \times 50 = 2500.$$

It will be seen that as an equality between these two numbers is approached, the product increases, reaching a maximum when the two are equal.

Consider a machine designed for 220 volts with an armature resistance of 0.2 ohm. Assume a counter e.m.f. of 209 volts. The effective e.m.f., the difference between 209 and 220, or 11 volts, would establish 55 amperes therein. The product of the armature current, 55 amperes, and the counter e.m.f., 209 volts, is 11,495 watts. This is the power which the motor converts and, neglecting the losses, delivers to the pulley. Assuming the motor to be loaded until its counter e.m.f. falls to 200, then to 150, 110 and 90, the corresponding effective e.m.fs. will go up in proportion to 100, 350, 550 and 650. Multiplying the armature currents by the corresponding counter e.m.fs., the power utilized in each case will be shown in the following table:

Impressed *e.m.f.*	Effective *e.m.f.*	Arm R	Arm I	Counter *e.m.f.*	Watts utilized
220	11	0.2	55	209	11,495
220	20	0.2	100	200	20,000
220	70	0.2	350	150	52,500
220	110	0.2	550	110	60,500
220	130	0.2	650	90	58,500

It will be observed that the power utilized increases steadily until the critical point is reached where the counter e.m.f. is 110 which is just one-half the impressed. Here the power utilized is a maximum of 60,500 watts. If the motor is still further loaded the armature current goes up to 650 amperes and the product of this current and the counter e.m.f. of 90 volts is only 58,500 watts.

The motor then develops a maximum power when its counter e.m.f. is just one-half the impressed. This application of the general law is not obtained by multiplying the two equal quantities, 110 volts effective, and 110 volts counter e.m.f., together, but by multiplying the armature current, 550 amperes, which is **proportional** to the effective e.m.f., and the 110 volts counter e.m.f. together.

Jacobi's Law is not a statement of efficiency as the efficiency of motors is proportional to their counter e.m.fs. When they are developing their maximum power, the efficiency would therefore be only 50% of the maximum.

It is not customary to ever load a motor until it does work at a maximum rate in accordance with Jacobi's Law. It is well, however, to know under what circumstances a machine may be made to develop a maximum power.

SECTION X — CHAPTER IV

DIRECT CURRENT MOTORS

MOTORS; SPEED; TORQUE; EFFICIENCIES

1. Upon what two factors does the output of a motor depend? What determines each of these factors?

2. Define "torque" in a motor. How is it measured? Give formula for same.

3. A motor runs 910 r.p.m. and develops a pull of 72 pounds on the circumference of a pulley having a diameter of 10 inches. How many h.p. does it deliver?

4. What class of work requires motors which will develop a constant torque and a constant speed? What kind of a motor fulfils these requirements and upon what kind of a circuit must it be operated?

5. What class of work requires motors which will develop a constant torque and a variable speed? What kind of a motor fulfils these requirements and upon what kind of a circuit must it be operated?

6. What class of work requires motors which will develop a variable torque and a constant speed? What kind of a motor fulfils these requirements? Upon what kind of a circuit must it be operated?

7. What class of work requires motors which will develop a variable torque and a variable speed? What kind of a motor fulfils these requirements and upon what kind of a circuit must it be operated?

8. If a series motor connected to a constant potential circuit is set to operate an exhaust fan, at what particular speed will it run? Explain fully.

9. Explain the performance of a shunt motor in driving a ceiling fan with the blades set at various angles?

10. Explain the performance of a street car on a level and on a steep grade when operated first by a series motor and second by a shunt motor.

11. A motor absorbs 20 amperes at 220 volts. Its commercial efficiency is 86 per cent. How many h.p. does it deliver?

12. Explain Jacobi's law of maximum work.

13. A motor is running at 115 volts and taking 7.4 amperes in its armature. Armature resistance is 0.32 ohm. What counter e.m.f. is being generated? Ans. 112.6 volts.

14. From the following data, compute the armature resistance of a motor: Impressed voltage = 220 volts. Counter e.m.f. = 214 volts. Armature current = 12 amperes. Ans. 0.5 ohm.

15. The armature of a shunt motor has a resistance of 2 ohms. The field has a resistance of 200 ohms. (*a*) What current will flow in the armature when 110 volts are applied to terminals with machine at rest? (*b*) Through field with machine at rest? Ans. (*a*) 55 amperes; (*b*) 0.55 amperes.

16. If the motor in the above problem were turning fast enough to develop 108 volts counter e.m.f., (*a*) what current would flow in the armature circuit? (*b*) In the field circuit? Ans. (*a*) 1 ampere; (*b*) 0.55 amperes.

17. A shunt motor takes a total current of 80 amperes from 115-volt mains. Armature resistance = 0.04 ohm. Field resistance = 60 ohms. (*a*) What current does each take? (*b*) What power is used up in heating the field and armature? Ans. (*a*) Field 1.92 amperes. Armature 78.1 amperes; (*b*) 0.466 k.w.

18. A 110-volt shunt motor has an armature resistance of 0.8 ohm. Field resistance = 220 ohms. Full load speed is 1,200 r.p.m. and the motor is taking 10 amperes. At what speed must this machine run as a generator in order to deliver 10 amperes at 110 volts? Ans. 1,390 r.p.m.

19. (*a*) In problem No. 18, what is the counter e.m.f. of machine when running at full load as a motor? (*b*) What is the e.m.f. produced when run as a generator and delivering 10 amperes at 110 volts? Ans. (*a*) 102.4 volts; (*b*) 118.4 volts.

20. A 550-volt series motor having 4 poles and 2 brushes, requires 180 k.w. at full load. Resistance of field and brushes together is 0.041 ohm. There are 350 active conductors on the armature. Armature resistance is 0.042 ohm. Speed is 600 r.p.m. What is the flux per pole? Ans. 7,500,000 lines.

21. A shunt motor which has an armature resistance of 0.2 ohm and a field resistance of 220 ohms draws 2.8 amperes from 110-volt line and runs at 1,000 r.p.m. If 55 ohms are added in series with the field, one ohm in series with the armature and the motor is loaded until it draws 20.4 amperes from the line, at what speed will the motor run? Assume that the field flux is proportional to the field current. Ans. 980 r.p.m.

DIRECT-CURRENT MOTORS

CONTROL OF ADJUSTABLE SPEED MOTORS

As has already been pointed out, practically all stationary machinery requires approximately constant speed motors for its operation. That is, when the load varies upon a given machine, the motor must not appreciably alter in speed. In certain cases, however, it is desirable to alter at will the fundamental speed of a motor, after which it is required that the motor shall not further vary in speed under variations in load. For example, consider a lathe turning a piece of metal, 3 inches in diameter: Assume that the speed is the maximum which the tool and work will stand without injury. If, now, the piece of work is removed and one 6 inches in diameter is substituted, unless the r.p.m. be changed, the cutting speed for the tool will be doubled with destructive results. It is, therefore, desirable to be able to adjust the speed of the driving motor to one-half of the original r.p.m. in order that the cutting speed shall be the same as before. This requirement has brought about a great variety of adjustable speed motors.

The speed of a direct current motor under a given load depends upon:

A. The e.m.f. applied to the armature.

B. The strength of the field.

C. The number of turns in series on the armature.

One or more of these methods, either separately or in combination, are always employed for the control of variable speed motors.

A. VARYING THE E.M.F. APPLIED TO ARMATURE

There are a number of methods of varying the e.m.f. applied to the armature of a motor.

Resistance in Armature Circuit

The oldest and most generally used consists in the insertion of a rheostat in series with the armature, Fig. 453. This allows the potential to be varied at the brushes while the field strength

may be held constant. This rheostat is more than a starting box. A starting box contains a wire which is designed to carry the current for a few moments only while the motor is accelerating. Should the lever be held on an intermediate point the box would soon burn up. The speed control box, *R*, is much larger and better ventilated, for it must be constructed so as to carry continuously the maximum current which the armature may require. This box may be used, however, in place of a starting box, in which case it should be provided with a no-voltage release magnet and provision must be made for insuring the effective operation of this release on any point of the box.

If the load upon the motor is such as to require a **constant current** in the armature, then, with a **field of fixed strength,** the **torque** developed will be **constant** under **all variations in speed.** The rheostat may now be employed to lower the impressed e.m.f. to any desired degree. Under these conditions with a **constant torque,** the **output will vary directly with the speed** and the **speed will vary directly with the e.m.f. applied.** Thus, if a 100 volt, 10 horse-power motor, with a given armature current, has the pressure lowered to 10 volts at the brushes and is thereby caused to rotate 100 r.p.m., it will develop say, one horse power. If the resistance in the rheostat is reduced and the e.m.f. is raised on the brushes to 30, 60, 80 and finally 100 volts, the speed will rise to 300, 600, 800 and 1,000 r.p.m. and the horse power developed will go up in the same ratio to 3, 6, 8, and 10 horse power.

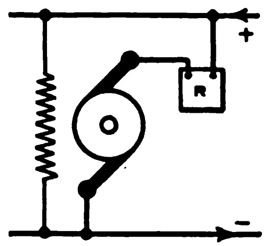


Fig. 453.—Resistance in armature circuit for varying speed of motor.

With a **constant armature current** and a **constant field strength** the **losses in** a shunt motor are practically **independent of its speed.**

With a rheostat in the armature circuit any number of different speeds may be obtained. The actual number will be limited only by the number of points on the rheostat. It is therefore a most flexible method of control. It is also a very simple arrangement to apply and is not expensive in first cost. Here, however, its advantages end, and from the standpoint of efficiency it is very poor.

Consider the case of a shunt motor requiring 40 amperes at 220 volts. If it is desired to reduce the speed one-half, it will be necessary to reduce the voltage from 220 to 110. A rheostat, therefore, may be inserted in series with the armature to absorb 110 volts. The resistance required will be

$$\frac{E}{I} = R = \frac{110}{40} = 2.75 \text{ ohms, in rheostat.}$$

The wire in the rheostat must be of sufficient size to carry 40 amperes, without excessive heating, and sufficient radiation must be provided to dissipate the heat generated.

If, while the motor was operating under these conditions at one-half speed, the load thereon was reduced so as to call for but 10 amperes instead of 40, the voltage reaching the motor would immediately alter. A current of 40 amperes, passing through 2.75 ohms, will effect a drop in potential of 110 volts, but a current of 10 amperes in passing through 2.75 ohms will cause only 27.5 volts drop. Subtracting this from the 220 volts of the line leaves 192.5 volts which will reach the motor. The result is that the speed of the motor will rise about 75%. Thus, when a rheostat is in series with the armature, the voltage lost in the rheostat changes with every change in load. This varying voltage subtracted from the line leaves a **varying voltage applied to the motor.** A shunt motor is only constant in speed so long as it is supplied with a constant potential. With the widely varying potential caused by the varying loads, a widely varying speed results. It will, therefore, be seen that **this method of speed control robs a shunt motor of its most valuable quality, namely, constancy in speed under variations in load,** because it deprives the motor of a constant voltage.

In considering the efficiency of this combination, let the resistance of the armature be 0.2 ohm, as stated; then 40 amperes multiplied by 0.2 ohm equals 8 volts, effective e.m.f. Subtracting this from 220 volts impressed gives 212 volts counter. To reduce the speed one-half it will be necessary to absorb one-half of 212 volts or 106 volts in the rheostat. 106 volts multiplied by 40 amperes equals 4,240 watts lost in the rheostat.

Assuming the field to take 1.2 amperes and the armature 40 amperes, the entire input into the motor will be 41.2 amperes.

41.2 amperes multiplied by 220 volts equals 9,064 watts absorbed from the line.

$$\frac{\text{Power lost in rheostat}}{\text{Power absorbed from line}} = \text{Per cent loss in rheostat.}$$

$$\frac{4240}{9064} = 46.7\%$$

$100\% - 46.7\% = 53.3\%$ of the absorbed power, which is all that reaches the motor. It may fairly be assumed that the motor itself will lose internally about 13% at half speed. Adding this to the 46.7% wasted in the motor, gives 59.7% of the entire power drawn from the line, wasted. $100\% - 59.7\% = 40.3\%$, which is the net efficiency of the combination of the above motor and the rheostat in the armature circuit when the speed is reduced to one-half normal.

It is evident that this arrangement is exceedingly uneconomical at low speeds. While the efficiency is high at high speeds, it falls in direct proportion to the reduction in speed and at very low speeds the losses are prohibitive. This is based on the assumption that the armature current is constant under variations in speed and a reduction in speed does not result in reducing the power drawn from the line. Therefore to reduce the speed 30%, by reducing the applied voltage 30%, the horse power is reduced from 10 to 7, and the 3 horse power of which the motor is deprived is simply transferred to the rheostat where it is converted into heat and wasted. If the applied e.m.f. is reduced 70%, the speed of the motor, and therefore the horse power developed, will be reduced 70%, or to 3 horse power. As 10 horse power is drawn from the line and only 3 utilized, 7 must be wasted in the rheostat. Speed reduction by this method is thus accomplished by taking the power out of the motor and wasting it in the rheostat, without reducing the amount drawn from the line.

H. Ward Leonard System

The second method of speed control, by varying the e.m.f. applied to the armature, is the H. Ward Leonard system, pictured in Fig. 454. Here, the adjustable speed motor, M', has its field supplied from an independent source via the mains L-L. The current for the armature is derived from a motor-generator set, M-G, commonly called the "power converter."

This is a direct-connected set, the motor, shunt wound, being directly connected to the mains, *L-L*, the set being kept in operation all the time. The field of the motor, *M*, is of constant strength and therefore the set operates at a constant speed. The generator, *G*, is separately excited from the mains, *L-L*, while the armature of this generator and the armature of the motor, *M'*, are connected on a local circuit electrically independent of everything else. Assuming that the rheostat, *R*, will open the circuit on the field of the generator, this machine will produce no voltage. The motor, *M'*, therefore, does not start. If the rheostat is now set so as to insert approximately 20 times the field resistance in series therewith, across the line, the generator *G* may develop say 10 volts. Being limited only by the ohmic

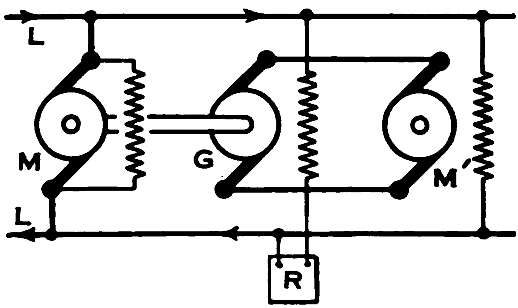


FIG. 454.—The H. Ward Leonard system of control using a motor-generator set to supply the armature of the industrial motor.

resistance of the circuit, this voltage is able to establish in the local circuit (which includes the armature of the motor, *M'*) a current of say 10 amperes. As this armature stands in a fully excited field it will develop sufficient torque to start. It will not rise very high in speed, however, because its counter e.m.f. will soon approach the 10 volts applied. To produce this power the motor *M* will take from the line 1 ampere at 100 volts, which, neglecting losses, is transformed at *G* into 10 amperes and 10 volts. The watts are the same in the two cases. The 10 amperes in *M'* will develop 10 times the torque that could be obtained if the 1 ampere in *M* were directly applied thereto. Had the system illustrated in Fig. 453 been used it would have been necessary to draw from the line through the rheostat *R*,

10 amperes instead of 1, and the pressure would have had to be reduced 90 volts through rheostatic loss. In the Leonard system the motor-generator transforms the high voltage and small current into a low voltage and large current, with corresponding increase in torque and without any rheostatic loss in the armature circuit. Notwithstanding the loss in the rheostat in the field circuit of the generator and the transformation losses, there is a great saving effected in the Leonard system over that where a rheostat is employed in the armature circuit.

To raise the speed of M' it is only necessary to raise the strength of the field of G by cutting resistance out of R. This may be raised in steps to 20, 30, 40 and eventually to 100 volts. The speed of M' will rise in direct proportion, and the input to the motor M is always in exact proportion to the actual power required.

This arrangement is, in effect, the equivalent of a variable gear ratio between M and M' with as many separate ratios as there are points in the rheostat R. This is illustrated in Fig. 455. Here let the input of 1 ampere at 100 volts at M be illustrated as a gear wheel, A, driving a gear wheel, B, which corresponds to the motor, M', but which has ten times as many teeth as A. The speed of B will obviously be $1/10$ that of A, but the turning moment or torque will be 10 times as great, which would be expected with 10 amperes. Next, suppose the rheostat R is partly cut out so as to raise the pressure of G to 50 volts. The reaction of this load on the motor M will cause it to demand from the line 5 amperes at 100 volts. This added power will make the generator supply the motor, M', with the same 10 amperes but under the increased pressure, which will now be 50 volts. This, in effect, is equivalent to shifting gears from low to intermediate on an automobile, and is equivalent to changing the gear wheel A for one, C, which has five times as many teeth in it. The speed of D will now be one-half the speed of C, but the torque of D will be twice the torque of C. If R is still further reduced until the strength of the generator G reaches full value, it may be assumed that G will generate 100 volts. The reaction on M will now cause it to take 10 amperes at 100 volts and will in turn cause G to deliver to M' 10 amperes at 100 volts. This is equivalent to shifting on an automobile from intermediate to high and in effect changes the gear wheel, C, to the gear

wheel, E, which contains the same number of teeth as F. The Leonard system then affords an hypothetical gearing between M and M' with a large number of ratios and the shifting from one ratio to another, can be made without any clutch or clashing

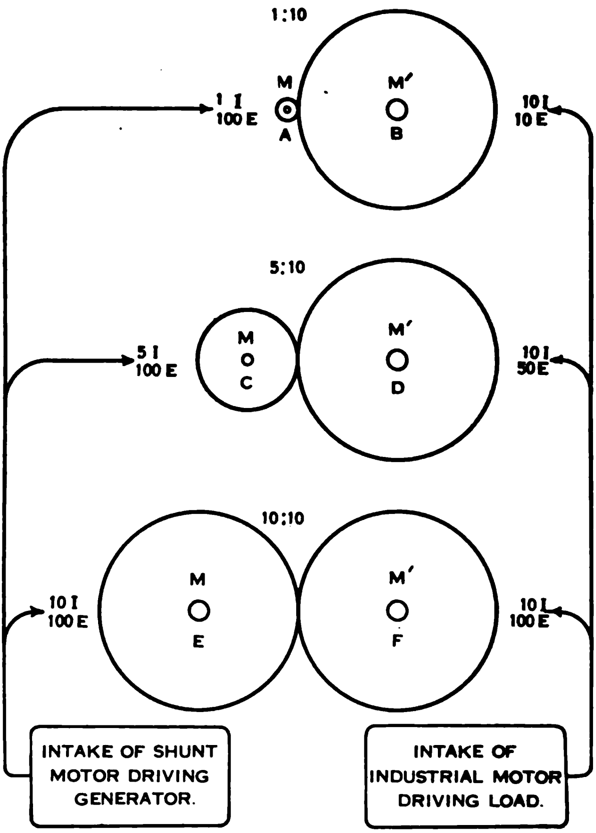


FIG. 455.—Illustration showing the variable gear ratio possible with the H. Ward Leonard system of control.

of gears, but as smoothly as a rheostat can be turned from one point to another.

It will be obvious that this system does not deprive the shunt motor of its constant speed qualities, under variations in load, for the voltage which G supplies M' is not altered by the current which M' demands, but is practically fixed by the field excitation of the generator, from the line.

The objection which may be offered to this system is its high first cost, as it requires an equipment of three machines, all of approximately the same kilowatt rating, to do the work which would be accomplished by the one machine shown in Fig. 453. For some applications, the interest on the high first cost, however, is largely if not wholly offset by the economy in operation experienced at low speeds, as the large rheostatic loss in the first scheme is entirely eliminated.

A special application of the Leonard system is found in a coal hoist, pictured in Fig. 456. Where coal is placed in storage, it is customary to have a bucket, having a capacity of a ton or more, hoisted by a cable, wound on a drum, and operated by a motor

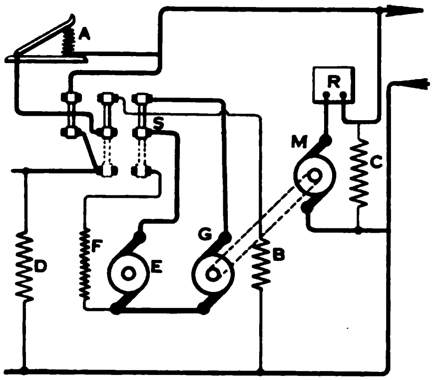


FIG. 456.—The H. Ward Leonard system adapted to a coal hoist showing circuits for raising and lowering the bucket.

or engine. When the bucket is emptied and released, the weight of the descending bucket, which is considerable, develops a large amount of energy. This energy is usually dissipated from a band brake, on the end of the hoisting drum. But it is not easy to continuously dissipate the required energy from an ordinary brake, and the result is that the brake may grab and the band burn. The Leonard system overcomes this difficulty and gives a very flexible control. One arrangement consists of a motor generator set, *M-G*, Fig. 456, where *R* is a starting rheostat, to start the set, and *S*, a three-pole double-throw knife switch to control the direction of motion of the bucket, and *A* is a foot operated rheostat to control the strength of the generator's

field, B. The field, C, of the motor, M, and the field, D, of the hoist motor are connected directly across the source of supply. To raise the bucket, the switch S is thrown into the position shown by the solid lines in the figure. Upon depressing A, resistance is gradually cut out of the field, B, which causes G to produce a rising voltage. This voltage is applied to the armature E, of the hoist motor. The speed at which the bucket is raised is wholly controlled by the pressure of the foot on A. The greater the pressure the higher the speed. When the bucket reaches the top of its travel, a reduction of pressure on A will lower the voltage of G, until the current delivered to E is just sufficient to produce a static torque which will hold the bucket stationary. As soon as the bucket is tripped, the switch S is thrown into the reverse position, shown by the broken lines in the figure. This cuts the rheostat, A, out of the field of the generator and into the field, D, of the hoist motor. The motor generator set now runs free during the descent of the bucket. A well ventilated rheostat F, having a resistance of about 1 ohm, is connected across the armature of the hoist motor, E, by the switch S. This armature, driven by the descending bucket, now becomes a generator, the output of which is governed by the excitation of D under the control of the field rheostat A. The reaction of this current in the armature on the field structure dynamically retards the speed of the descending bucket, which can be governed at will. The greater the pressure on A, the more the braking effect is applied, for this strengthens D and causes E to produce more current in the 1 ohm rheostat F. The heat can be radiated far more uniformly from a well-ventilated rheostat, F, than from a brake band. The system is smooth, rapid and efficient in its operation.

Modified Leonard System

One of the difficulties with the Leonard system is that the greatest current for the motor, M', is required at the start when its speed and therefore the voltage of the generator G is a minimum. This current is required when the field of G is weakest and the large armature current will produce a maximum distortion and possibly destructive sparking at the brushes. Fig. 457 represents a modification of this system which has been designed to overcome this difficulty. Here the armatures of the generator G and

the industrial motor M', instead of being on a local circuit by themselves, are in series with each other across the main source of supply. When the motor, M', is to be started and requires but 10 volts from a total line pressure of 100 volts, the field of G is at its greatest strength and is thus better able to resist the effect of armature reaction. The e.m.f. generated by G is opposed to the line voltage so that if M requires 10 volts and the line furnishes 100, G will furnish an opposing e.m.f. of 90 volts. To accelerate M' the field of G is weakened. This increases the difference between G and the line, which is applied to M', and as M' rises in speed the current falls, and when the field of G is weakest the current through M' is a minimum. An interesting

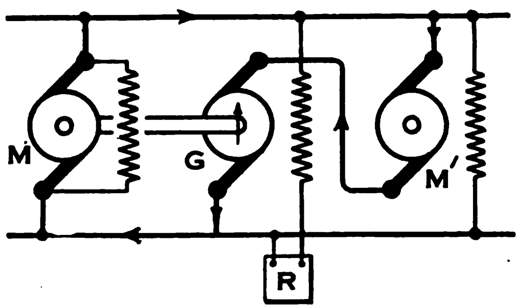


FIG. 457.—Modification of the Leonard system of control to avoid having field of generator weak when industrial motor has its largest current at start.

feature of this plan is that the functions of M and G are reversed. The current from the line through M and G makes G a motor. The power which it develops, transferred through its shaft, changes the shunt motor, M, into a generator, and makes it deliver power to the line, which is in parallel with the principal source, and thus helps supply the current which M' and G absorb. The introduction of the commutating poles on both motors and generators cares for sparking in the original Leonard system so as to make this modified system unnecessary.

Crocker-Wheeler Multi-Voltage System

The fourth method of varying the voltage at the brushes for the purposes of variable speed control is the Crocker-Wheeler multi-voltage system with motor-balancers, illustrated in Fig.

458. Here the main generator, G, furnishes current at 250 volts to the lines, L_1 and L_2. A set of machines of equal kilowatt capacity but wound for different voltages is connected across these mains. The shafts of these machines are all direct connected to each other. The armatures are electrically in series and the fields are in multiple across the mains. When no power is required at the load these machines float as motors on the line, absorbing practically no current and generating a counter e.m.f. practically equal to the line voltage across their terminals as indi-

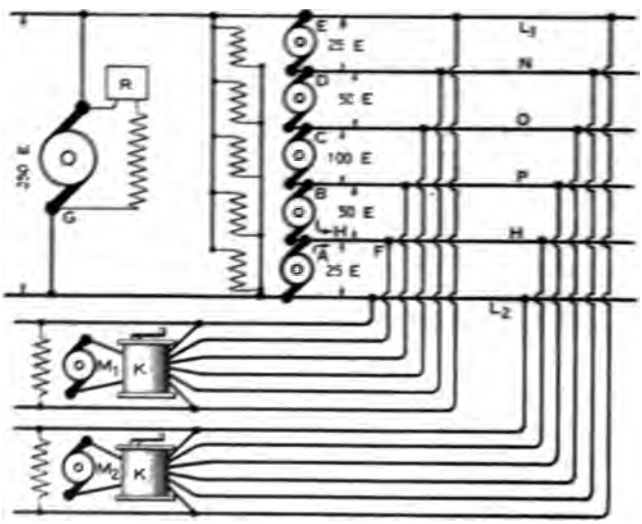


FIG. 458.—The Crocker-Wheeler system of motor balancers for variable speed motors.

cated. The adjustable speed motors, M_1-M_2, have their fields directly connected across the mains. Their armatures may be connected across any one generator in the set or any number in series, by means of controllers K. To obtain the lowest speed on the motor, M_1, its armature is connected across the terminals of A. The difference of potential across this machine is 25 volts. Current will immediately flow to M_1. This current will cause the potential between H and L_2 to drop slightly. The counter e.m.f. of A now exceeds the drop across it and it becomes a generator, furnishing current over wire F to the motor M_1. As A is now a generator requiring power, it reacts

through its shaft connection upon the machines *B-C-D* and *E* calling for more power. The set is slightly reduced in speed and more current comes from the generator *G* down through *E-D-C-B*. Here it is diverted over the wire *H* where it joins in parallel with the current from *A* to the motor M_1. Similarly the variable speed motors may have their armatures connected across any one or any combination of the machines of the set in series. When so connected that machine or series of machines automatically become generators while the rest in the series automatically become motors, supplying the power to drive

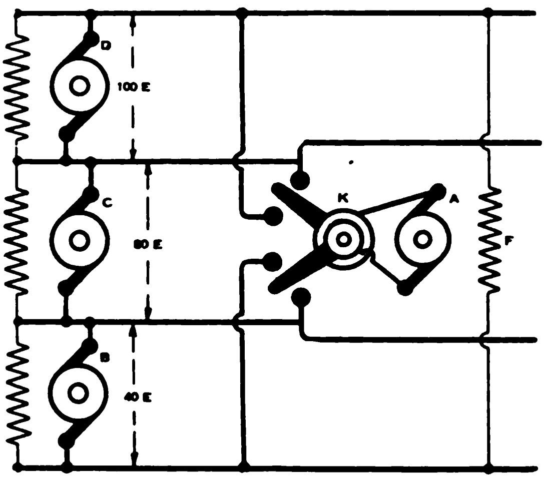


Fig. 459.—A multi-voltage system of control for variable speed motors employing three generators of different voltages.

those which are generators. If armatures of the various industrial motors are connected across all of the wires L_1-*N-O-P-H*-L_2 in series, then the power for these armatures is practically all drawn from the main generator and is distributed between the industrial motors in series. The motors *A-B-C-D-E* then become balancers and serve only to hold the potential at the proper value on the wires *N-O-P-H*, and prevent any fluctuation in the voltage on the industrial motors.

In most instances three machines in a motor-balancer set instead of five are sufficient to produce a satisfactory number of fundamental voltages. Singly, or in combination, six different

voltages could thus be obtained. An advantage of having two sources of the same voltage as shown in Fig. 458 is that one-half of the industrial motors can be connected upon each of the two 25 volts sources for the lowest speed.

Similar results could be obtained by having three generators connected in series, as shown in Fig. 459, in which case the motor-balancers should be omitted. Here the controller *K* serves to connect the armature *A* across any one of the sources *D*-*B*-*C*, or any number of them in series. The field, *F*, of the industrial motor is permanently connected across the two outside lines. The Crocker-Wheeler system is preferable because the first cost would be less and the efficiency greater for one 300-kilowatt machine than for three 100-kilowatt machines. While the motor balancers would be required in the former case, and would not be necessary in the latter, it would be necessary to use a cable consisting of four wires from the generating plant to all of the industrial motors, as in Fig. 459, whereas but two wires from the power plant are necessary in Fig. 458, and the motor balancer may be located directly at the load, which may be some considerable distance from the power station. Furthermore, the cost of wires for low potential, and the drop therein, would be excessive for long distances.

Double Potential Source

Another method of varying the potential at the brushes of the industrial motor is by the use of the three-wire generator, Fig. 460. This machine has already been explained in a previous paragraph. By means of slip rings and balance coils, externally connected, a single direct-current machine is made to furnish two fundamental voltages. The industrial motor may have a rheostat in its armature circuit giving say 10 steps of speed, while connected across wires furnishing 125 volts. It could then be switched to the 250-volt mains and the same rheostat employed to give 10 additional steps of speed. A two-voltage three-wire generator will thus double the number of separate speeds which could be obtained by means of a rheostat in the armature circuit, with one voltage.

B.—FIELD CONTROL

The second general scheme for adjusting the speed of a direct-current motor is by varying the field strength. While the speed

of a motor **varies directly** with the **potential applied to the brushes,** it **varies inversely** with the **strength of the field flux** across the armature.

While the **output** of a motor with a constant field strength varies **directly** with the **voltage applied** to the armature, provided the **armature current is constant,** the **output** of a motor with **field control** is **constant at all speeds provided the armature current is constant.** This **constancy of output regardless of speed** comes about in the following way:

When the field is weakened, more current flows in the armature coils. This increase in current in the armature is much greater in proportion than the decrease in the field strength.

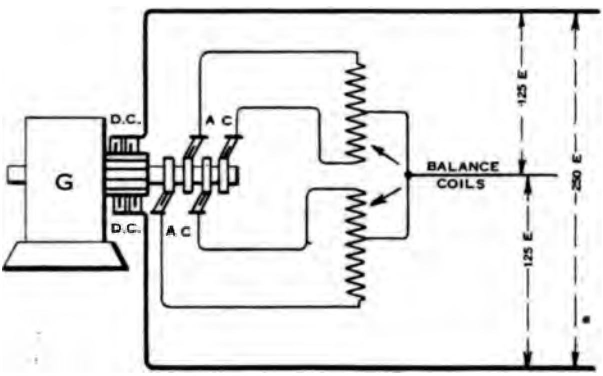


FIG. 460.—The three-wire generator showing circuits from neutral through balance coils.

This is because a **small per cent reduction in field strength** brings about a **large per cent increase in effective e.m.f.,** due to the low armature resistance. The actual torque developed then becomes greater and the armature rises in speed until a balance is obtained. If the current increased only to the extent that the field decreased, the product of armature current and field strength would remain constant, and there would be no gain in torque and therefore no increase in speed when the field strength was lowered. Therefore the unexpected condition prevails, in that **a shunt motor runs faster with a weak field than with a strong field.** Nevertheless, if the armature current is constant, the output of a shunt motor with field control is constant at all speeds. To demonstrate this fact, consider the

following example: If the field flux is reduced one-half, the counter e.m.f. falls one-half. The armature will then receive several times as much current as before. If the load permits, the armature will rise in speed to double its original value, when it will again develop its original counter e.m.f. This will reduce the armature current to the same value as at first. As the field is reduced one-half while the armature current is the same as at first, the torque, which is proportional to the product of the strength of the armature and the strength of the field, is reduced to one-half. As the speed has been doubled and the torque halved, the output is the same as at first.

Practically, with almost any kind of a load on a motor, the resistance of the load will increase when the speed at which it is driven rises, therefore the result of weakening the field is to cause the motor to take more current, which in turn causes it to accelerate in speed and to develop more power. It must be emphasized that the power of the motor is a constant quantity at various speeds **only provided the armature current is constant.**

If a non-commutating-pole motor has its speed varied, by the insertion of a rheostat in the field, as in Fig. 461, it will be found that the speed cannot be increased more than about 25% before destructive sparking sets in, due to the large armature current reacting on the weakened field. The addition of commutating poles to motors made field control a practical success and permitted an increase in speed to about five times the lowest speed obtained with full field strength, without objectionable sparking. As in a generator, the commutating pole plays two distinct parts. First, it resists armature reaction, and thereby prevents field distortion. Second, it supplies a flux through the armature coil short circuited by the brush and effectually reverses the current therein.

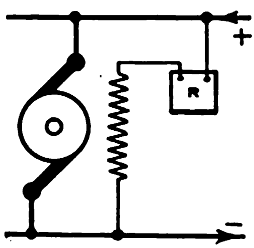


FIG. 461.—Speed control of shunt motor by resistance in field circuit.

Fig. 462 represents the normal flux distribution between the field pole faces and the armature in a machine running at full speed at no load and with full field strength. The flux is concentrated somewhat at the center of the poles and tapers off

toward the pole tips. The distribution is uniform, however, on all pole tips.

If the machine is subjected to a load, it slows down, absorbs more current in the armature circuit and armature reaction sets in. This condition is shown in Fig. 463. Here the armature actually succeeds in producing a cross flux. The effect of the armature's cross magneto-motive-force is to oppose and therefore weaken the flux at the pole tips *A* and *B* and to strengthen

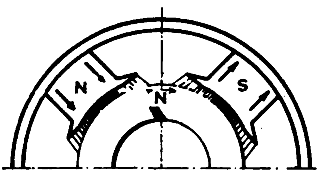


FIG. 462.—Flux distribution in shunt motor at no load without commutating poles.

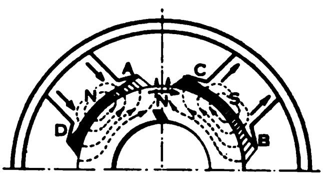


FIG. 463.—Flux distribution in shunt motor without commutating poles, when loaded.

it at the pole tips *C* and *D*. This disturbs the uniform distribution of the field flux across the pole face as shown. In a non-commutating pole machine the flux under the tips *A* and *B* is relied upon for reversing the current in the coil short circuited by the brush. By designing the machine with a field which is sufficiently strong, this commutating fringe of flux can be main-

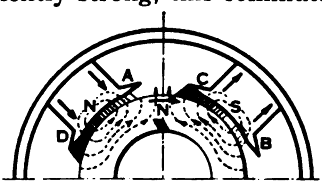


FIG. 464.—Flux distribution in shunt motor without commutating poles when field strength is weakened to accelerate speed under load.

FIG. 465.—Flux distribution in shunt motor with commutating poles when field strength is weakened to accelerate motor under load.

tained even under heavy load. If, now, it is attempted to raise the speed of this motor by weakening the field, the conditions shown in Fig. 464 will result. The flux under the pole tips *A* and *B*, already weakened through armature reaction, now disappears entirely and no fringe is available as an aid to commutation. The result is the motor sparks at the brushes.

Fig. 465 shows how this is overcome by the aid of the commutating pole. By inserting between the main poles, another

pole, with a magnetizing coil arranged to produce a magneto-motive-force diametrically opposed to the cross magneto-motive-force of the armature, the effect of armature reaction in this region may be counteracted. In addition thereto this coil produces an actual flux in the proper direction through the short-circuited armature coil and insures the reversal of the current therein entirely independent of the main field flux from the tips *A-B*. The main field flux may now be weakened to a very considerable degree without affecting commutation, because the commutating pole winding, being in series with the armature, produces a magneto-motive-force which counter-balances armature reaction in the interpolar region at all loads and in addition produces a flux through the short circuited coil in the armature in proportion to the armature current, and therefore insures the reversal of current in said short circuited coil. Fig. 466 shows wiring connections for a commutating pole motor with a reversing switch, properly connected for variable speed control. Fig 467 shows the relative sizes of machines having the same output, with and without commutating poles.

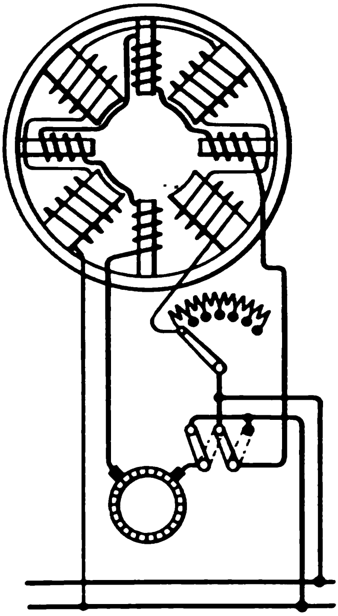


FIG. 466.—Circuits through shunt and interpole windings of commutating pole motor arranged for speed control by varying strength of shunt field circuit. Reversing switch for reversing direction of current in armature and commutating pole winding when reversal of direction of rotation is desired.

The core of the commutating pole winding is usually worked at a very low saturation, for this pole actually produces but a small flux. Because the saturation is low, the flux will vary in almost exact proportion to the current in the winding. It therefore

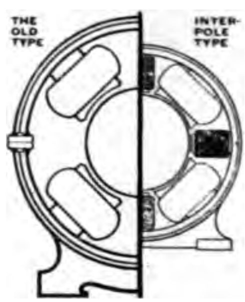


FIG. 467.

compensates for the varying requirements under wide changes in load.

If the commutating pole winding is made with an excessive number of turns, the main field flux may be reduced, if so desired, through the effect of the commutating pole flux alone at heavy loads. This would result in an actual increase in speed with an increase in load. As ordinarily designed, the commutating pole motor has a drooping characteristic similar to an ordinary shunt machine. This characteristic is practically unaffected in form by the actual speed at which the motor is adjusted to run.

The main field need not be nearly so intense in a commutating pole machine as is necessary in a non-commutating pole machine of the same horse power. In fact, the copper required for the commutating pole is practically saved from the shunt field winding, so that the total copper in a commutating pole machine might be no greater than that in a non-commutating pole machine of the same horse power.

For manufacturing reasons it is often desirable to use only half as many commutating poles as main poles. In a four-pole machine with four commutating poles, each coil undergoing commutation is cutting the flux from the two commutating poles nearest to each other, one on each coil side. If one-half of the commutating poles are removed, each coil undergoing commutation will be cutting flux from one pole only. In order to produce proper commutation, it is only necessary to sufficiently increase the magneto-motive-force of the two remaining commutating poles, which will thereby enable the other two to be dispensed with. The actual amount by which the ampere-turns must be increased is only about 25 or 30% of the ampere-turns on each of the poles omitted. This is because the two interpole windings which remain, need to compensate for double commutation flux only and not for double armature reaction.

The functions of the winding on the commutating poles of an electrical machine are as follows:

1st. To neutralize the armature reaction flux in the region between the main poles.

2d. This reaction flux being neutralized, to establish in that same region a flux in the opposite direction and of such a value that a voltage is generated in the conductors under commutation equal and opposed to the reactance voltage in those conductors.

Where the number of commutating poles is equal to the number of main poles, about 70% of the entire winding on the commutating poles is required to neutralize the armature reaction flux and make possible the establishment of the corrective commutating flux by the remaining 30%. Where the number of commutating poles is one half the number of the main poles, it is still necessary to neutralize the reaction flux **but only in ONE magnetic circuit. This being neutralized, only 30% increase in turns is required on the commutating pole to produce 100% increase in the corrective flux to reverse the current in the short-circuited armature coil.** The flux from these commutating poles has two magnetic paths in parallel and of the same reluctance—one through the next main pole of the same magnetic polarity, the other through the next main pole of the opposite polarity and on the other side. In one case the main flux is boosted and in the other the main flux is lowered. The effects compensate each other except under conditions of saturation where the pole in which the flux is boosted no longer increases its flux in proportion to the current, while the pole in which the flux is bucked is still reduced in proportion. This brings about a weakening of the total flux.

Where the number of commutating poles is one-half that of the main poles, the return paths for the flux being of equal reluctance and in parallel, one part of the field yoke is worked at a higher density than the other since the commutating flux reduces the density on one side and boosts it on the other.

Some interpole motors possess a peculiar tendency to hunt, that is, to oscillate in speed. It is brought about in the following way: With a weakened field, the first effect upon the motor under an increase in load is to cause the armature to slow down. The current rises and the armature reacts strongly on the already comparatively weak main field. This batters down the main field flux, which still further reduces the counter e.m.f. This causes a further increase in armature current and consequently a still further reaction on the main field with another reduction in counter e.m.f. The current surges still higher as the demand under increase in load is cumulative. This large increase in current causes an abnormal rise in commutating pole flux, which tends to saturate the yoke in portions of the field frame. This causes

the shunt field flux, already greatly weakened, to fall still further as the armature current continues to rise. After a certain interval, however, the armature begins to accelerate under this abnormal current and the counter e.m.f. goes up with it. There is a certain critical point under an increase in speed where the armature current reaches its maximum. When this point is reached, a surge of speed upward begins and with it the current commences to go down. The speed finally reaches a maximum when the current is a minimum and the reverse action sets in. If the armature is light, hunting is not apt to occur; where its inertia is great, hunting may take place.

A differentially compound motor will race, in case of heavy overload due to the great reduction in field flux caused by the large current in the series field. In fact such a motor may start in the wrong direction under the initial rush of current because of the series field overpowering the shunt. This tendency is enhanced by the inductance of the shunt winding which will retard the current's rise. In this case the motor may revolve in the wrong direction until the counter e.m.f. and torque fall to zero. The armature stops, but a heavy current is flowing through armature and series winding. By this time the shunt field has reached its proper value, and the machine starts in the right direction. But if the initial current is sufficiently great, the series winding may overpower the shunt so as to bring about another reversal of flux and consequently of rotation. A similar state of affairs may arise in the case of shunt motors with commutating poles, if the brushes are not properly placed. Thus, if the brushes are shifted backward, the commutating poles will produce a magneto-motive-force in opposition to the main poles and will cause the same tendency to reversal of direction of rotation that was observed in the differentially compound motor. The reverse is also true where the brushes are given a forward lead on a commutating pole motor; the flux will be increased and the speed reduced. If actual reversal of direction does not occur, a pulsation of speed or hunting may result, for since the effect of a backward displacement tends to weaken the field, there will be a corresponding decrease of counter e.m.f. and an increase of armature current, which will produce an acceleration of the armature. The increased current further strengthens the commutating poles and further weakens the resultant field.

This of course accelerates the armature. The counter e.m.f., however, is proportional to the net flux and to the speed. The tendency on the part of the armature to accelerate will then continue until the decrease of counter e.m.f. due to reduced flux is offset by the increase due to greater speed. The decrease of field strength cannot, however, go on indefinitely, because the commutating poles eventually become saturated, but up to the time they saturate, the speed increases continuously and the momentum of the armature will cause the speed to continue to increase even after the flux has reached a practically constant value. This will be particularly true if the armature possesses considerable inertia. The result will be a rapid increase of counter e.m.f. even exceeding the line voltage, in which case the machine becomes a generator, drawing upon its energy of rotation to send current back into the supply line. The speed under these conditions would rapidly fall, causing a reduction of counter e.m.f. so that the armature current will again rise, thereby producing increased speed so that the cycle of change continues.

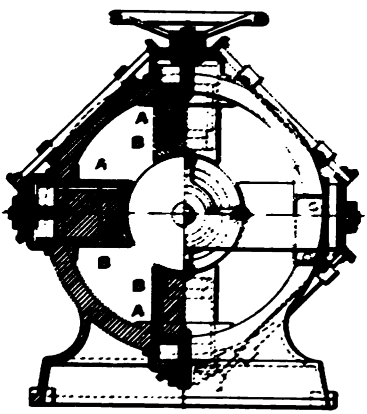


FIG. 468.—Section of Stow variable speed motor. Speed control is obtained by varying the reluctance of the magnetic circuit. Geared wheel on top withdraws plungers from center of magnet cores.

Stow Motor

Another method of varying the field strength is the Stow motor, Fig. 468. Here the field core, B, has a plunger, A, of large diameter, which is moved in and out, introducing an air gap between the armature and the end of the plunger which may be varied at will. Withdrawing the plunger introduces an added reluctance which lowers the total flux and increases the speed. The fringe from the pole tip, however, upon which commutation depends, is maintained at the requisite density. This air gap is also interposed in the path of the cross armature flux, thereby preventing armature reaction from disturbing the

commutating flux. No field rheostat is used and a 5 to 1 ratio of speed is obtained. The four plungers in a four-pole machine are all mechanically geared together so that they may be simultaneously manipulated by a hand wheel on top of the motor. The commutating pole machine with a field rheostat as a method of control is preferable if the motor is to be controlled from a remote point.

Lincoln Motor

Another method of varying the speed of a motor by varying the field strength consists in moving the armature out from

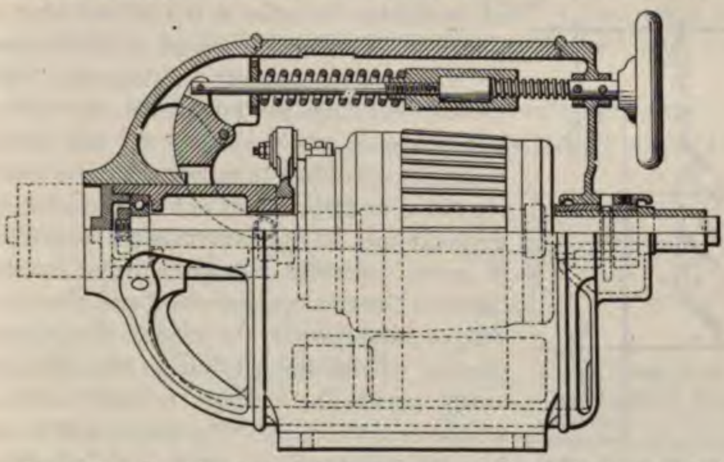


FIG. 469.—The Lincoln variable speed motor. Hand wheel is provided for shifting armature on its shaft longitudinally in the field frame. The armature is tapered, thereby producing a magnified variation of magnetic flux for a comparatively small longitudinal movement.

between the pole pieces, thereby reducing the armature surface subjected to the field flux. By making the armature of smaller diameter at one end than at the other and the field poles to correspond, a considerable range of field flux may be obtained by a comparatively small lateral movement of the armature, see Fig. 469. To provide the necessary commutating fringe the pole tips upon which commutation depends, are extended.

C.—Changing Number Armature Conductors in Series

The **third** fundamental method of varying the speed of a motor is by altering the number of conductors in series on the armature. The possible number of armature windings is limited

to two. These may terminate in two separate commutators. Any relation may exist with reference to the capacity of these two windings. It is customary to make the two windings duplicates. This permits them to be operated singly, in series, or in multiple. A motor will have its greatest capacity when the two armature windings are connected in multiple, but the speed will be the same with the windings used singly or in parallel. For a **fixed field strength,** and **brush voltage,** the **speed varies inversely with the number of conductors in series.** Two duplicate windings in parallel would have the same number of conductors in series as would one winding singly. Therefore the speed is unchanged. As the ampere capacity is doubled, when the two windings are in parallel, the torque and therefore the capacity of the motor will be double that obtained with one winding alone and the speed of the motor will be a maximum. If the windings are connected in series, the line voltage will be divided between the two commutators, and the speed will be halved, while the current drawn from the line will be halved, but as the windings are in series, the current in each winding will remain the same. The torque will therefore be the same as when both windings were in parallel, but as the speed has been halved the horse power output of the motor will likewise be halved. A motor so constructed therefore has two fundamental speeds, one being half of the other. Its output, however, is reduced at half speed to one-half of its maximum horse power, but this is accomplished without the loss which is encountered when a rheostat is inserted in the armature circuit.

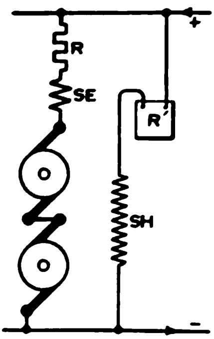


FIG. 470.—Low speed obtainable on double commutator motor with two armatures in series and series fields supplementing shunt fields and added resistance in armature circuit.

If ability to operate the windings in parallel and so obtain their combined capacities is not essential, three fundamental speeds may be obtained, by giving each winding the same current carrying capacity but employing a different number of conductors in each winding, thus proportioning them for different speeds. The speed of the armature will vary inversely with the number of conductors in series, therefore the **greater the number of con-**

ductors in series, the less the speed. Consider such a motor designed with two windings, one arranged to produce 1,500 r.p.m. and one giving 1,000 r.p.m. The windings differ; the first, giving 1,000 r.p.m., must have one and one-half times the number of conductors possessed by the winding giving 1,500 r.p.m. With the two windings in series, the total number of conductors will be 1 plus $1\frac{1}{2}$ or $2\frac{1}{2}$ times the number of conductors producing 1,500 r.p.m. The speed with the windings in series would therefore be 1,500 divided by $2\frac{1}{2}$ or 600 r.p.m. If the winding having the highest speed contained 100 conductors, the other winding would possess 150 conductors and give 1,000 r.p.m., while the two windings in series would have 250 conductors and give 600 r.p.m.

It would be impracticable to place the two windings above referred to in parallel because they contain unequal numbers of conductors in series, and therefore are adapted for different voltages. This would cause one to tend to receive current and the other to deliver current resulting in a circulating current in the windings. Fig. 470 illustrates the application of this scheme of control. Here the two armature windings are connected in series with each other, and with a series field winding, *Se*, and a rheostat, *R*. The series winding aiding the shunt winding, insures a maximum field strength, the rheostat *R* lowers the voltage, reaching the armature, and this voltage is finally halved at the brushes. This will insure a large starting torque and at the same time give a speed of about 5% of maximum. The motor is accelerated by means of a controller, which first cuts out *R* in a series of steps and then cuts out the series field, *SE*. Next the two armatures are reconnected in parallel as shown in Fig. 471, and a sufficient number of sections of the rheostat *R* are inserted in series across the line to prevent too great a jump in speed. This is then again cut out through a number of steps until the armatures are in parallel across the line. A number

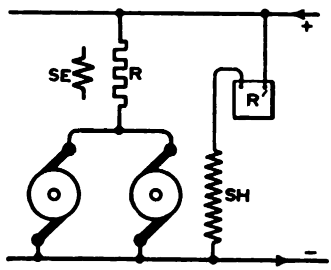


FIG. 471.—Highest speed with double commutator motor obtained with two armature windings in multiple. Resistance *R* is gradually cut out of armature circuit and resistance *R'* cut into field circuit.

of additional steps of speed are then obtained by inserting resistance R' in the shunt field.

Speed Regulator for Shunt Motor

When it is desired to have a motor operate at a closer approximation to constant speed under variations in load than can be obtained by the design of a shunt motor, an automatic regulator may be attached which will improve the speed characteristics. The scheme for this regulator is pictured in Fig. 472. A centrifugal switch, S, is carried on the end of the shaft, the contacts being normally held open by the spring, P. Slip rings and

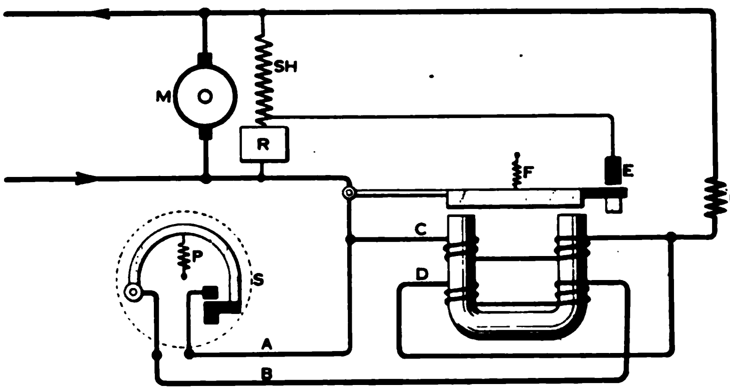


FIG. 472.—Automatic regulator for holding speed of shunt motor constant under variations in load.

brushes are provided to connect these contacts through wires A and B to the external circuit. A differentially wound relay has two windings, C, and D, opposed to each other magnetically, which are connected through a small adjustable resistance, R, across the line. The rheostat R is in series with the shunt field SH, of the motor, whose speed is to be regulated. The armature of the motor M is across the line. When the speed is low the spring P holds the contacts of the centrifugal switch open. Winding D of the relay is therefore open. Winding C being across the line attracts the armature and the contacts E are held open. Rheostat R is therefore in series with the shunt field. As the field is weakened the armature accelerates. When it reaches the limit for which the regulator is adjusted, the centrifugal force closes the contacts at S against the tension

of the spring P. Winding D is thus energized. This makes the relay differential and the armature is released. Under the tension of the spring F, the contact E closes, which short-circuits the field rheostat R. This strengthens the field of the motor and causes its speed to drop. Should the speed lower too much the contacts in S open and the rheostat R is automatically reinserted in the line. A very fine adjustment of the centrifugally operated switch insures that the motor shall be held at a close approximation to constant speed under considerable changes in load.

SECTION X CHAPTER V

DIRECT-CURRENT MOTORS

CONTROL OF ADJUSTABLE SPEED MOTORS

1. What is the effect upon the speed, torque and output of a shunt motor when the voltage is varied at its brushes while the armature current and field strength are held constant?

2. What are the advantages and disadvantages of varying the speed of a shunt motor by means of resistance in series with the armature?

3. Show by diagram the H-Ward-Leonard system of variable speed control. Explain in full its operation and advantages.

4. Sketch and explain the H-Ward-Leonard system applied to a coal hoist.

5. Show by sketch the modification of the H-Ward-Leonard system of variable speed control for the purpose of improving commutation in the generator at all speeds of the motor. Explain in full its operation and advantages over the original Leonard system.

6. Sketch the Crocker-Wheeler multi-voltage system for variable speed control. Explain in detail its operation.

7. Explain the way in which the motor and generator functions of a motor-balancer set are automatically reversed according to the demands of industrial motors on the Crocker-Wheeler multi-voltage system of variable speed control.

8. Sketch three generators of suitable voltage for operation in series for variable speed control. Tabulate the various fundamental speeds that can be obtained.

9. Explain the application of the three-wire generator for variable speed control.

10. What is the effect upon the speed, torque and output of a shunt motor if the field strength is varied, while the armature current and brush voltage are held constant?

11. What are the relative advantages and disadvantages of varying the speed of a shunt motor by means of resistance in the field circuit?

12. How does the field strength effect the torque of a motor if the armature current remains fixed? How does the armature current affect the torque of a motor if the field strength remains fixed? If both of these quantities are varied, how and to what extent will the torque be varied?

13. Explain the principle, construction and advantages of the commutating pole motor.

14. Explain the principle of the Stow variable speed motor.

15. Explain the principle and construction of the Lincoln variable speed motor.

16. Explain the advantages of a double-commutator motor with two equal armature windings.

17. Explain the principle of an automatic regulator for maintaining the speed of a shunt motor more closely. Sketch.

DIRECT-CURRENT MOTORS

AUTOMATIC MOTOR ACCELERATORS

Where large motors are to be started, it is desirable to have some form of automatic accelerating device for bringing the motor rapidly up to speed. Small motors are of course usually started by means of manually operated starters, but difficulties are encountered when a large motor is so operated. With a manually operated starter, the handle is thrown over by hand and the magnitude of the accelerating current is determined by the judgment of the operator. If the operator is careless or his judgment is poor, he may cut out the starting resistance too rapidly, with the result that the motor receives excessive current. This imposes an abnormal load on the line and may injure the motor electrically and mechanically. If, on the other hand, he is over cautious, too long a time may be involved in accelerating the motor. Where motors are to be started and stopped many times a day, as in the case of elevators or in steel mills, time is an important factor. If the motor is to be reversed, the difficulties encountered are increased. There is always a safe maximum current permissible for starting a motor. In order that the motor shall not be overtaxed, this current should not be exceeded. In order that time shall not be wasted, the motor should always receive the maximum current which it can safely stand during acceleration. That is, an ideal accelerator must automatically interpret the conditions of the load.

Among the types of control which have been developed to automatically accelerate motors, are: the time element type, the counter e.m.f. type, the shunt current limit type, and the series current limit type.

In the **time element type,** a solenoid; *S*, Fig. 473, wound for line voltage is connected across the line by the operator's switch. The current now passes through the shunt field, which is across the line and through the armature in series with the starting rheostat *R*. The solenoid moves the lever of the rheostat *L* upward, its rate of travel determined by the dash pot, *D*. The time required for the cutting out of the starting resist-

ance is thereby governed. This is entirely independent of the conditions of the load. It is therefore necessary to adjust the dash pot so that the motor will not receive more than its maximum safe current under the conditions of heaviest load. It does not permit the motor to accelerate more rapidly when the load is light. In certain classes of work this may not be objectionable, but the controller cannot interpret the load conditions because the resistance is cut out at a fixed rate under all circumstances. The disadvantage of the time element system is chiefly due to trouble with the dash pot.

Individual magnetic switches have been used to replace the solenoid, each switch being provided with a dashpot which will determine the time of its operation.

A very successful type of time element device consists of a cylindrical drum, driven by a pilot motor through a worm gear.

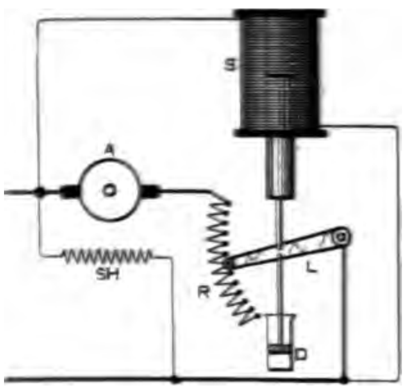


FIG. 473.—Automatic motor accelerator of the "time element type" in which rate of cutting out of resistance in series with armature is accomplished in a definite time governed by the setting of the dash pot *D*.

Here, the time of acceleration is adjusted by changing the speed of the pilot motor. Segments are provided on the drum for short-circuiting sections of the starting resistance. The circuits of the motor are opened or closed by a magnet contactor. The motor-operated drum short-circuits the armature resistors during acceleration. The advantage of this plan consists in its simplicity. The acceleration is smooth, under all conditions of

load and the motor will start with an overload as the time element device gradually reduces the resistance until the torque of the motor is sufficient to start the load. Excessive current can be guarded against by proper setting of the circuit breaker.

In the **counter e.m.f. type** of starter, Fig. 474, closing the main switch places the shunt field across the line. In parallel therewith is placed the armature *A*, in series with the starting resistance *R*. The solenoid (the core of which is attached to the lever *L* of the starting box), instead of being connected in shunt with the line, is connected in shunt with the armature *A* and is therefore responsive to the armature voltage, which is prac-

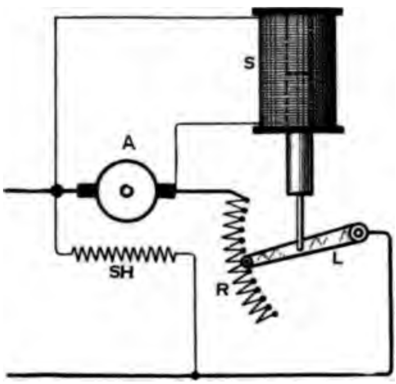


FIG. 474.—"Counter e.m.f. type" of motor accelerator in which cutting out of resistance in series with armature is governed by the counter e.m.f. of armature which determines the extent to which solenoid *S* is excited.

tically the same as the counter e.m.f. If the initial rush of current is so great that the armature will not start, the resistance *R* will not be cut out, for the ohmic drop across the armature is so low that the solenoid *S* is virtually short-circuited thereby. If, however, the load is within the capacity of the motor's torque, the armature will start. In so doing it generates a counter e.m.f. which increases the drop across the brushes. This will very soon cause *S* to be sufficiently energized to start moving the lever *L*, thereby cutting out sections of *R*. As *A* accelerates, *S* has a rising voltage impressed upon it which in turn accelerates the rate at which *R* is cut out. This counter

e.m.f. type of starter therefore interprets the load requirements and successfully protects the motor. This has a distinct advantage over the time element type which begins cutting out resistance immediately, even though the motor is seriously overloaded.

A simple diagram of a counter e.m.f. starter employing one magnetic contactor for short-circuiting the starting resistance is shown in Fig. 475. The closing of switch 1 is accomplished by a push button. This connects the motor in line in series with a resistor. One end of the operating coil of this switch is connected to the negative side of the line and the other end is connected through a push button to the other side of the line. The coil of switch 2 is connected across the motor armature and will

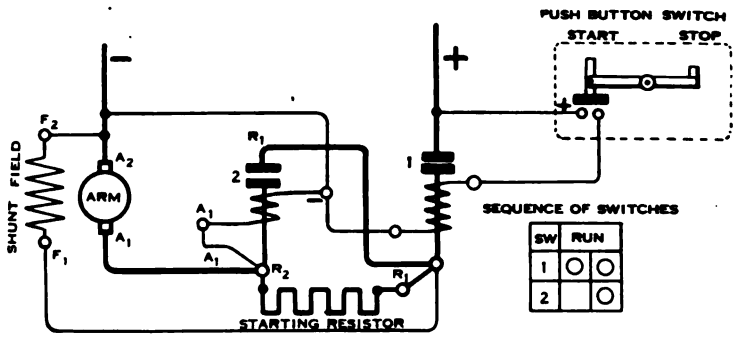


FIG. 475.—Automatic motor accelerator of the "counter e.m.f. type" in which electro-magnetic contactors replace solenoid.

therefore operate only when the counter e.m.f. reaches a predetermined value. A disadvantage of this arrangement is that if switch 1 is opened by pushing the stopping button, switch 2 remains closed, held by the counter e.m.f. until the speed falls to about 25% of maximum. If, before switch 2 is opened, the starting button is again pushed, the motor will be thrown on the line without any starting resistance, possibly resulting in a severe shock. To avoid this, an interlock is usually provided on switch 1 which opens the coil of switch 2 whenever switch 1 is opened. An improvement of this design is shown in Fig. 476. Here all of the coils are alike and the interlock on the last switch is superfluous. The operating coils of all the switches are connected on one side to the motor brush farthest away from the starting resistor. The other sides of all the coils are connected to taps on

the starting resistor, the coil on switch 1 being connected to the point R_2 on the resistor. The voltage on this coil is equal to the line voltage, minus the drop through the first section of the resistor. As the motor rises in speed the counter e.m.f. lowers the armature current. This reduces the drop in the first section of the resistor. The voltage on coil 1 therefore gradually rises until this switch closes. Switch 2 has its coil connected to R_3. The voltage on this coil is increased by the closure of switch 1. The increase in current, however, causes a considerable drop in the second section of the starting resistance. As this current gradually decreases with the rising speed of the motor, switch 2

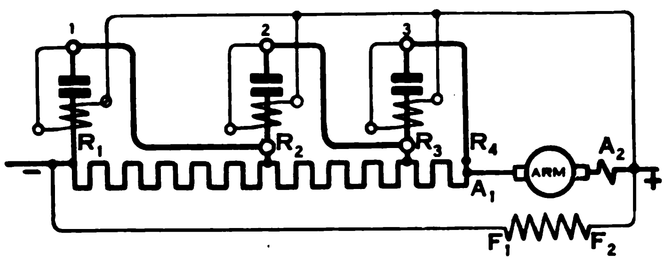


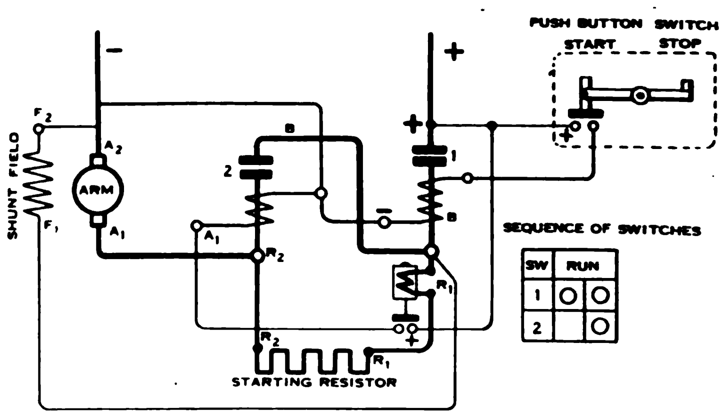
FIG. 476.—Automatic motor accelerator of the counter e.m.f. type in which the energizing coils of the contactors are connected across different sections of the starting resistance and therefore energized at different potentials.

closes. Switch 3 is connected across the motor armature and operates when the counter e.m.f. is nearly equal to the line voltage.

The counter e.m.f. type of starter has been widely and successfully used in connection with elevator controls. A disadvantage is found, however, if the line voltage is subjected to great variations. An increase in line voltage will cause S, Fig. 474, to operate sooner than it should and a drop in line voltage sometimes prevents S from operating at all. These are extreme cases, however. With reasonable constancy of voltage these difficulties are small.

The principle involved in the **shunt current limit type** is a relay having a series winding which holds the relay contacts open when the current is above a predetermined value. When the current falls sufficiently, the relay armature closes the circuit to the shunt coil of a magnetic switch. A series relay is

provided for each contactor. The relay contacts are normally held open mechanically, until the electric circuit is closed with the maximum resistance in series. The relay armature is then released, and is allowed to drop when the current is reduced to the value for which the relay is set. The drop of the armature completes the circuit for the operating coil of another contactor which in turn short-circuits a section of the starting resistance. Fig. 477 illustrates a control of this type. Pushing the button closes a circuit for switch 1. Immediately under the contactor is a series relay whose contacts are connected to the positive line and through the operating coil of switch 2 to the nega-



SW	RUN	
1	O	O
2		O

FIG. 477.—Automatic shunt current limit type of motor accelerator with contactors controlled by series relay which determines the time when starting resistances shall be cut out.

tive line. When the relay armature is released, these contacts close, thus operating switch 2. When switch 1 is open, the relay contacts are held open by a spring. When switch 1 is closed, the spring is released mechanically, so that the contacts may close. The current in the series coil, however, holds the armature up and the contacts open, until the current falls to the predetermined value. The armature then drops and the contacts close. This will not take place until the motor has nearly attained full speed, so that when switch 2 closes and short circuits the starting resistor, the increase in current will be limited.

The advantages of the current limit type of controller employing shunt connected contactors controlled by series relays

are: **First,** the sections of the starting resistor are short circuited only when the rising counter e.m.f. has reduced the **motor current** to a predetermined value, for each successive step. **Second,** this method is not affected by variations in line voltage provided there is sufficient voltage to close the contactors. **Third,** the load under which the motor will start is limited. If the load is too great to allow the motor to accelerate sufficiently to reduce the current to the predetermined value, the relay will not drop and close its contacts, therefore the starting resistance will not be cut out.

The disadvantages of the method are, **First,** it may result in too rapid acceleration of the motor under load. **Second,** additional apparatus is required, namely, a relay for each contactor. **Third,** the motor may fail to start under overload. While this may be an advantage, in some cases it may be a disadvantage. The system has proved very reliable in heavy service with frequent operation.

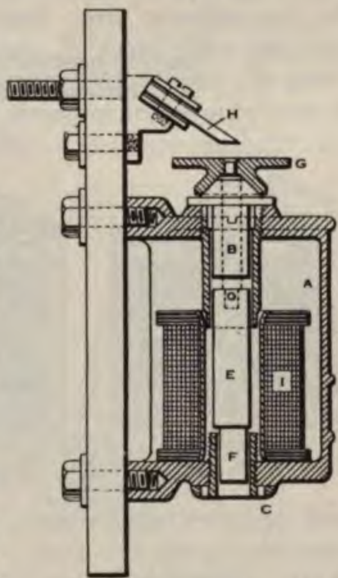


FIG 478.—Automatic series lock-out switch of the Electric Controller and Manufacturing Company for the control of resistance in armature circuits of motors.

The series current limit type is so called because the magnetic switches which control the acceleration of the motor are **series wound,** and their windings are connected in series with the motor to be started. This type of controller is made possible through the design of a most unusual type of magnetically operated switch. This switch acts not only as a device for closing the circuit and holding it closed, but also as a current limit relay. If the current which flows through the winding of the switch is below a certain critical value, the switch will close instantly, while if the current is above this critical value, the switch will will lock out, or refuse to close until the current has been reduced to the point for which the switch has been set. Fig. 478 shows the construction of one form of this switch. Here I is the operating coil of heavy wire adapted for connection in series

with the motor to be controlled. The winding surrounds a brass tube, within which the core E moves freely in a vertical plane. The upper end of the core carries a non-magnetic stud B, to which is attached a copper plate, G, arranged to make contact with a pair of contact brushes, H, when the switch is closed. The lower end of the core E is reduced in cross-section at F, and forms a shoulder where it unites with E. The stem F passes into a hollow, adjustable soft iron tube, C. The winding is enclosed by a cylindrical iron casing which affords a return for the magnetic flux. Surrounding B is an iron tube which does not quite reach E, the air gap between E and this tube being the only break in the magnetic circuit. When a current flows through I the magnetic flux bridges the gap between E and the tube surrounding B, the lines tend to shorten themselves

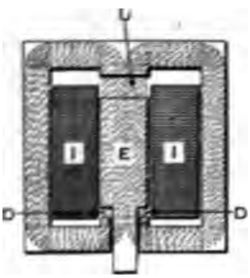


FIG. 479.

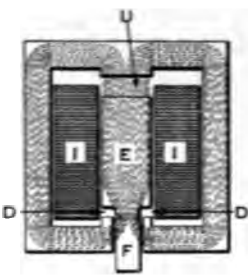


FIG. 480.

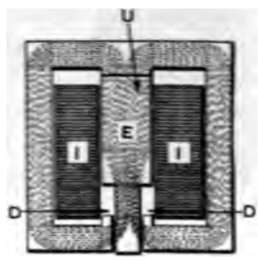


FIG. 481.

and the switch tends to close. At the lower end of the core, however, the flux has two paths. One of these is from the iron frame A into the sleeve C, and from the upper edge of this sleeve through an air gap D, Fig. 479, into the shoulder of the core. This portion of the flux produces a magnetic pull downward; that is, it operates to prevent the closing of the switch. The second path for the flux is through the sleeve C horizontally to the portion of the plunger F at right angles to the direction of motion, thence upward through E, Fig. 480. This portion of the flux is not effective in producing a downward pull on the core E. The total flux divides between these two paths inversely as the reluctance. With a small current in the actuating coil, practically all of the flux passes horizontally into F, as this path is of much less reluctance than the other one. The cross-section of F, however, is restricted, and as this portion becomes saturated the

reluctance of the path increases, and the flux is finally crowded into the vertical path, whence it is obliged to cross the air gap to the shoulder of E, Fig. 479. The core E is then acted upon by two forces, one of which tends to close the gap at the top and the other composed of the weight of the moving parts, plus the

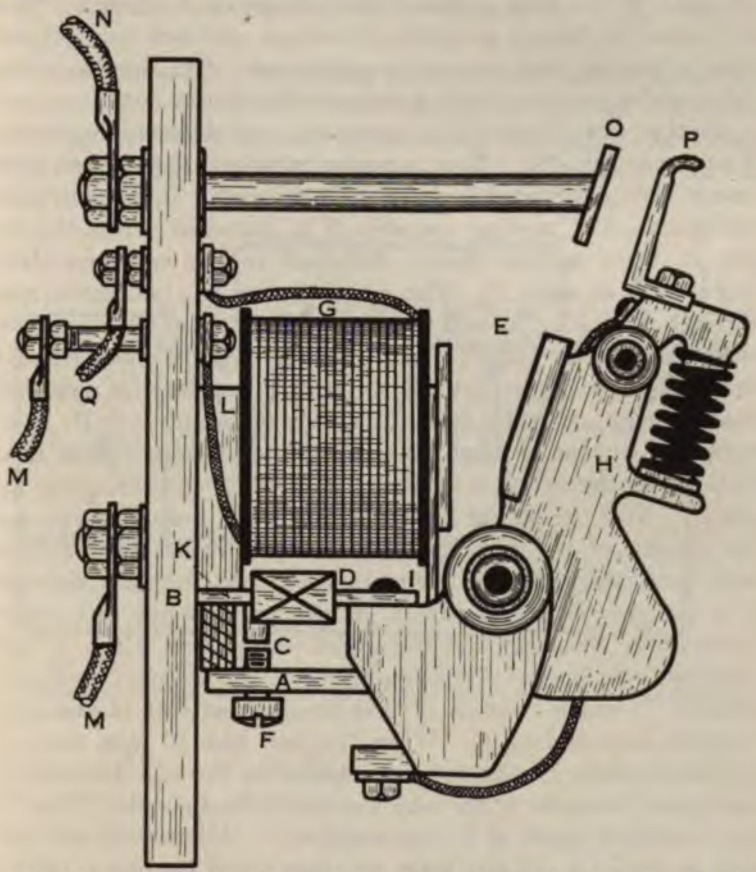


FIG. 482.—Automatic series lock-out switch of the Westinghouse Electric and Manufacturing Company for governing the rate at which resistance is cut out of the armature circuit of a motor.

downward magnetic pull at the shoulder of the plunger. When the current is below a certain critical value the upward pull is greater than the downward pull plus the weight of the moving parts, and the switch will close, Fig. 481. When the current is

above this critical value the downward pull plus the weight of moving parts predominates and the switch cannot close. Fig. 479. The critical point below which the switch will close and above which it will lock out is adjusted by screwing the plug, C, Fig. 478, up or down, which adjusts the length of the lower air gap. If the plug is raised, the air gap is shortened. This decreases the current at which the switch will lock out. If the plug is lowered, the air gap is lengthened. This increases the value of the current at which the switch will lock out.

Another switch similar in principle, but different in design is shown in Fig. 482. Here, a magnetizing coil, G, is wound with coarse wire and placed in series with the motor to be controlled as before. The moving member H is attracted across the air gap E, when current flows. Attached to this same member, however, is an arm, A. The magnetic flux has two paths, one through H, I, K, L, G and the air gap E. It also has a by-path through H, A, air gap C, K, L, G and E. With a small current the path of the flux is entirely through K, and little or none will pass through A. The switch then closes promptly. If, however, the current is large, the path K is saturated with flux. This causes the overflow of flux to pass via A and across the air gap C. Now the pull of the lever A upward toward K opposes the closing of the switch, and when this overflow of flux is sufficiently large, the switch locks open. As the path through K is the shorter one, it might be inferred that the flux would always take this path and the switch would close before it had time to lock open. This is prevented by a massive copper damper D which consists of a short-circuited coil of one convolution surrounding K. When the flux tries to rush through K, the reaction of the induced current in the coil D forces it back, and compels it to take the path through A. Thus, if the current is large, A is first energized. If, however, the current is within the closing limit, the flux which was momentarily forced through A will gradually find its way via the shorter path through K and the switch will close. Thus, the flux through K is always delayed, and the flux which locks the switch open through A is allowed to predominate, if there is any excess flux. An adjustable iron screw, F, allows the air gap C to be varied. This will alter the value of the lock-out current.

A simple controller employing switches of either of the above

types is shown in Fig. 483. K is the starting switch closed by the operator to start the motor, and opened to stop. The acceleration is entirely automatic. Switches S_1, S_2 and S_3 are of the type described above and control the starting resistance R. The switches are provided with series wound actuating coils C_1, C_2 and C_3. C_3 is also provided with a shunt wound holding coil, H_3.

When the switch is closed by hand, current flows through the armature and series field of the motor and through the entire starting resistance R and the actuating winding C_1 of switch S_1 to the negative side of the line. The shunt field F of the

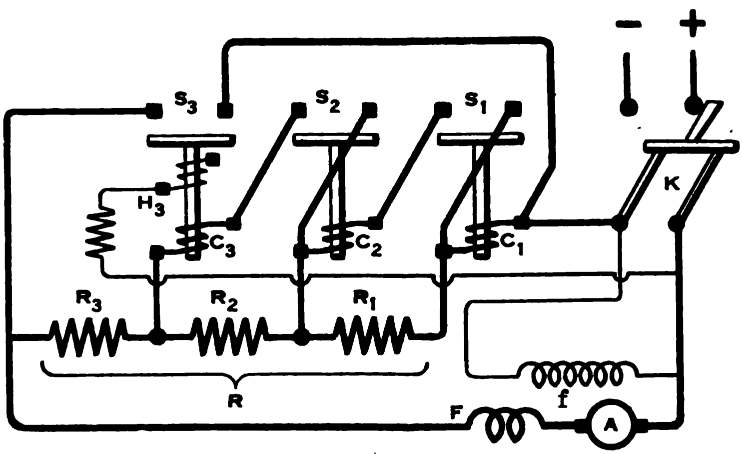


FIG. 483.—Schematic diagram of circuits through starting resistance, motor circuits and series lock-out switches for automatically accelerating heavy duty compound motor.

motor having been simultaneously energized when the main switch was closed, the motor should start. But, although the winding C_1 of switch S_1 is energized, this switch will not close until the current has dropped to the value for which the switch is adjusted. If the motor starts, its counter e.m.f. will gradually reduce the initial current until it reaches the value for which S_1 was set. Then, and not before, S_1 will close. This causes section R_1 of the starting resistance to be short-circuited and the current passes through armature, series field and sections R_3 and R_2 of the starting resistance, thence through the coil C_2 and across the contacts of S_1 through the coil C_1 to the negative side

of the line. The rise in current, due to the operation of S_1 is sufficient to cause S_2 to lock out. The second switch, therefore, cannot close until the motor has again speeded up and its current fallen to the value for which S_2 is set. Then S_2 closes. This cuts out section R_2 of the starting resistance, and energizes coil C_3. This switch now locks open, until the increased current is again backed down to the value for which S_3 is set. When this takes place, S_3 closes. This short-circuits the path through S_1 and S_2 and they drop open. At the same time, holding coil H_3 is thrown across the line to keep switch S_3 closed. This coil acts likewise in the capacity of a no-voltage release, severing the connection between the line and the motor, in case the current fails from any cause. To stop the motor, it is only necessary to open switch K.

When current limit acceleration is employed, relatively few subdivisions of resistance are required compared with manually operated starters. Up to motors of 5 horse power, satisfactory performance is insured with but a single accelerating switch.

In addition to starting, these series current limit switches provide an effective arrangement for permitting dynamic braking, the same switches being employed to limit the braking current. Thus the armature of the motor may be connected directly across the starting resistance through the accelerating switches when it is desired to stop. As the motor, acting now in the capacity of a generator, sends a large current through this braking resistance, the current limit switches lock open, but as the motor slows down under this braking tendency, the current falls and the switches become operative, closing in sufficiently rapid succession to hold the braking current up to the maximum safe value. This will insure the stopping of the motor in the minimum time. The series lock-out switch is satisfactory for starting service where the motor to be accelerated is always loaded. The disadvantage of the system is the possibility of the switches dropping open with light load. The shunt holding coil on the last switch will generally prevent this.

SECTION X CHAPTER VI

DIRECT-CURRENT MOTORS

AUTOMATIC MOTOR ACCELERATORS

1. Explain the principle of the "time-element" type of automatic motor accelerator. Where may it be used?

2. Explain the principle of the "counter-e.m.f." type of automatic motor accelerator. Sketch. Where may it be used?

3. Explain the "counter-e.m.f." type of automatic motor accelerator with electro-magnetic contactors.

4. Explain the automatic type of motor accelerator with electro-magnetic contactors controlled by series relay.

5. Explain the automatic "series-lockout" switch designed by the E. C. & M. Co. Sketch.

6. Explain the automatic "series-lockout" switch designed by the Westinghouse Company. Sketch.

7. Sketch a compound motor, starting resistance and series accelerating switches for automatic acceleration.

DIRECT-CURRENT MOTORS

REVERSING MILL MOTORS

The reversing rolls in steel mills were originally operated by steam engines. When it became possible to install electrical power for all purposes in these mills, some radical changes in the design of motors intended to operate the rolls were necessitated.

Electrical operation of steel mills is now almost universal, because of the economy and reliability of operation and the fact that the layout of the mill can be made much more convenient with electrical drive than with steam drive.

Steel ingots about 18 inches by 20 inches by 50 inches, weighing about 8,000 pounds, and heated to a temperature of 2,200 degrees F., are moved on a roller table toward a pair of steel rolls resembling a mammoth clothes wringer, called the **blooming mill.** The ingot is passed through the bloomer rolls 18 or 20 times, the upper roll being lowered a little by a special motor at each pass. The ingot is finally reduced to a strip, 3 inches by 8 inches by 60 feet long. The power required for the operation of the mill is enormous, and the rolls must be reversed with great rapidity, often 30 times a minute, for the steel must be worked while it is hot. It is in the operation of this mill that the electric drive has its greatest advantage, and the peculiar design makes possible a commutating motor which will start, accelerate to full speed, develop 15,000 horse power, stop, reverse and develop full speed in the reverse direction, all in three seconds and yet commutates satisfactorily.

The equipment for this purpose consists of a reversing motor and a flywheel motor-generator set, together with exciters and control equipment.

Referring to Fig. 484, *IM* is a 3,000 horse power induction motor drawing power from the alternating current mains, *ACM*, and direct connected to a 5,000 kilowatt generator, *G*. Between these two machines and mounted on the same shaft is a flywheel, *FW*, weighing 90,000 pounds. The speed of this induction motor is controlled by a "slip regulator," which inserts a

resistance, *WR*, in the secondary circuit of the motor and slows it down when a demand for more power is made upon it.

The armature of the generator *G* is connected electrically in series with the armature of the reversing motor *RM*. In this circuit is connected the series field, *Se*, of the exciter, supplying the variable field *V.P.* of the reversing motor, *RM*.

There are two exciters, connected to, and driven by, an induction motor *M*. The shunt exciter, *Sh. Exc*, supplies the constant potential field, *C.P.*, of the reversing motor *RM.* through the field rheostat *R′*. It also supplies the field *F* of the generator *G*, through the regulating and reversing rheostat *RR*.

The series exciter, *Se. Exc*, supplies the variable potential

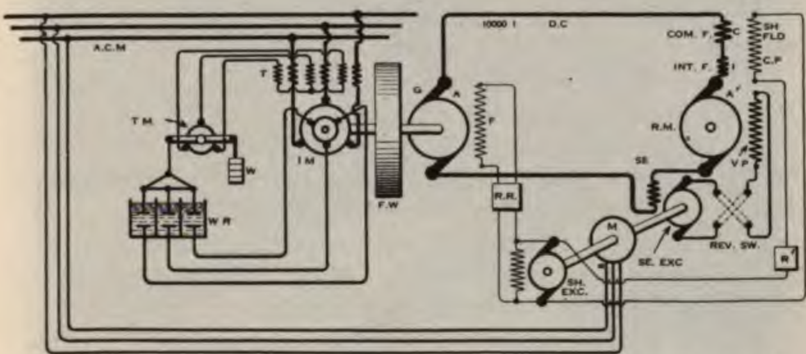


FIG. 484.—Heavy duty reversible mill motor used in steel mills with fly-wheel motor-generator set for supplying power.

field *V.P.* of the reversing motor *RM*, and gives this machine the characteristics of a compound motor. When the current in the armature of *RM* is reversed, the series field, *V.P.*, the strength of which must be proportional to the armature current, must have its polarity reversed to keep its direction the same as that of the constant potential field, *C.P.* Now, if this field were directly in series with the armature, it would be necessary to reverse connections in the circuit *D.C.*, which often carries as high as 10,000 amperes, and this would be beyond the practical limit of almost any reversing switch. By interposing the series exciter, a reversing switch may be connected as shown, where the current is only about 100 amperes, which can readily be handled. Electro-magnetic switches are, of course, used here.

The general scheme of operation is as follows:

The motor-generator and the exciter sets are running. The reversing motor *RM* is standing still, with full excitation on its constant potential field *C.P.* The master controller handle rests in the off position.

If, now, the master controller handle is moved either way, the reversing motor *RM* revolves in a direction and at a speed depending upon the position of the handle. The motor *RM* is rapidly accelerated to normal speed by gradually increasing the generator field excitation, *F*, up to full voltage through *RR*, which is operated by the handle of the master controller. Still higher speeds for use when the steel bar becomes greatly lengthened may be obtained by weakening the motor field *C.P.*, through rheostat *R′*, which is also operated by the master controller.

As the steel ingot strikes the rolls and the load on the motor *RM*, increases, the e.m.f. of the series exciter *Se.Exc* increases, due to the increased current in the main circuit, and the exciter field *Se*. This increases the field strength of the reversing motor *RM*, causing it to slow down, thus decreasing the strain both on the motor and on the mill. The increased field thus obtained also increases the torque which *RM* develops and which is required for excessive loads due to cold metal, etc.

The motor, *RM*, is stopped by dynamic braking. When the handle of the master controller is moved toward the off position the field *F* of the generator *G* is weakened. This lowers the e.m.f. of the generator below the counter e.m.f. of the motor *RM*. The motor *RM* now becomes a generator, and power flows from *RM* to generator *G*, causing it to motor. *G* now speeds up, due to the power imparted to it, and energy is stored in the flywheel as it is accelerated. The reaction of the load of this 90,000-pound flywheel on *G* is in turn handed back to *RM* and brings the reversing motor quickly to rest.

The field *F* is now reversed by the operation of the master controller on *RR*, and *G* commences to build up its e.m.f. in the opposite direction. As the current in the main line reverses, the variable field connections *V.P.* of *RM* are reversed and the main current rapidly rises to as high as 10,000 amperes if necessary.

The load on the reversing motor may vary from nothing to

15,000 horse power. The load on the A. C. mains, *A.C.M.*, is held practically constant at about 3,000 horse power. The smoothing out of this enormous load into a steady input of comparatively small value is accomplished through the equalizer

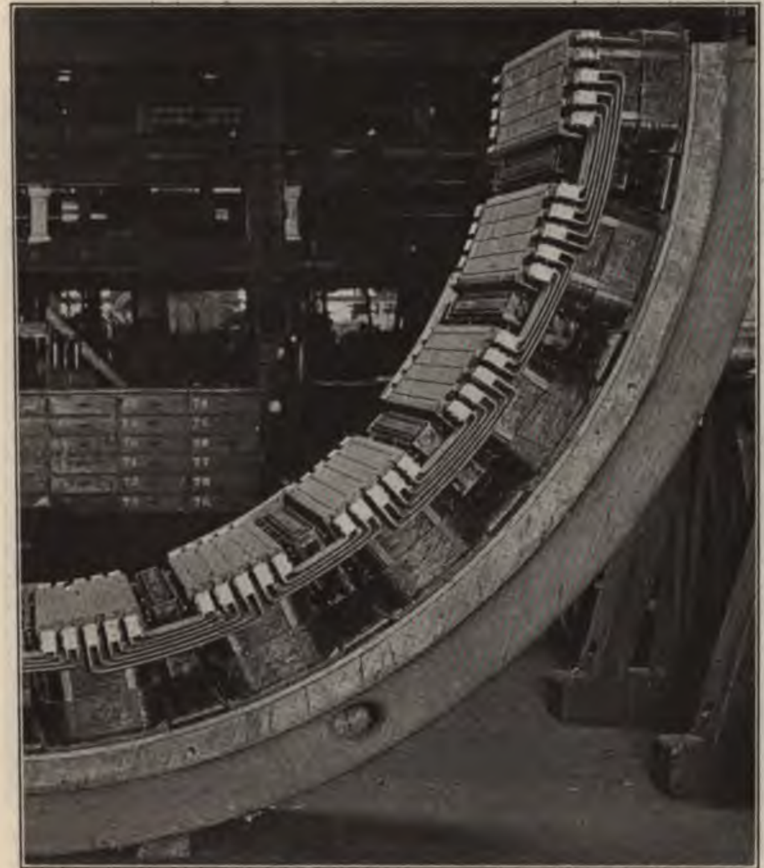


FIG. 485.—Section of field of Westinghouse reversing mill motor showing main poles, location of compensating winding and commutating poles.

set, consisting of the motor-generator and flywheel. When the load, accompanying reversal, comes on *RM*, additional power is demanded. This causes the induction motor *IM* to slow down slightly, demanding more power. The incoming current from *A.C.M.* to this motor flows through transformers *T*

which energize a **torque motor,** *TM*, forming a part of the **slip regulator.** The torque motor separates the electrodes in a liquid rheostat, *WR*, thus inserting resistance in the secondary of the main induction motor *IM*, which promptly slows down considerably. As the main induction motor *IM* thus "lies down on the job," and refuses to respond to the demand of the generator *G* for more power, the flywheel must supply the required power.

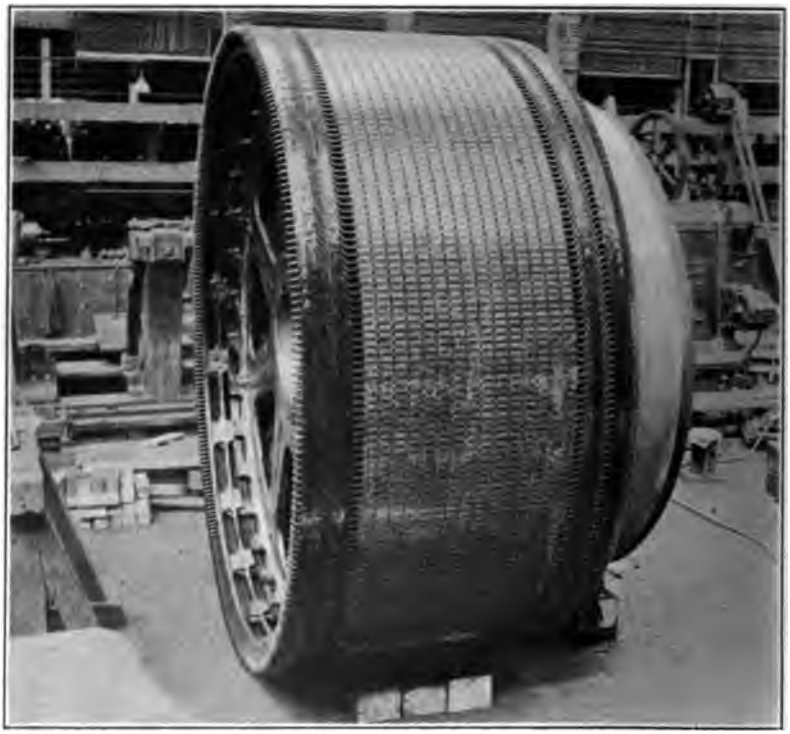


FIG. 486. -Complete armature and commutator for one end of Westinghouse reversing mill motor shown in Fig. 487.

Now remember that the flywheel had been speeded up, storing energy in stopping the reversing motor *RM*. It now responds, returning to *RM* as much as 70% of the energy absorbed originally in stopping *RM*. The peak of the load is thus supplied by the flywheel, without taking excessive current from the A.C. mains. If the slip regulator is set to operate at average load, the induction motor will operate at this load continuously, the

flywheel alternately absorbing and giving up energy in excess of the average demand.

The reversing motor *RM* is of special proportions and unusual design. It is built either as a single unit or as a double unit. Single units are rated at 8,000 horse power and double units, virtually two motors with two commutators on one bed plate, at 12,000 horse power or more. This machine has four field windings. The first is the constant potential field, *C. P.*, already referred to, supplied by the shunt exciter. The strength of this

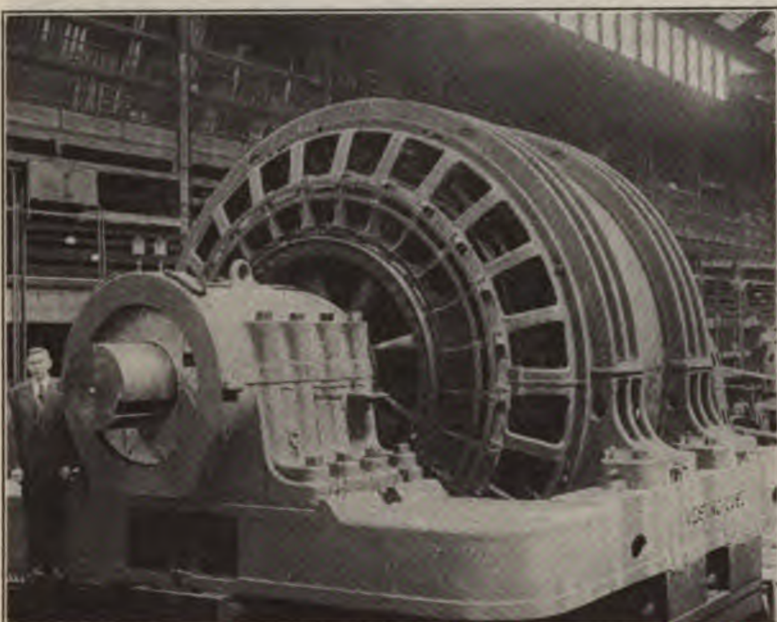


FIG. 487.—15,000 horse power peak rating 600 volts on each end, double Reversing Blooming Mill Motor, 0-120 r. p. m. in each direction. Built by The Westinghouse Company.

field is only varied to obtain the highest speed. The second is the variable potential field, *V.P.*, referred to, supplied by the series exciter and giving the motor the characteristics of a compound machine. The third is the commutating pole field, *I*, used to produce a commutating flux. With an ordinary motor this field would be sufficient to prevent sparking, but the conditions here are very severe. The load on the reversing motor

fluctuates very rapidly, successive peaks being only two or three seconds apart. When the load is thrown on, the enormous current sometimes reaching as high as 10,000 amperes, may be sufficient to completely overpower the commutating pole and actually reverse the flux in it, at the same time establishing a strong leakage flux, which would cause destructive sparking. It is therefore necessary to make special provision to insure sparkless commutation. The cause of sparking which accompanies severe load fluctuations here is the shifting of the main magnetic field, due to the changes in armature magnetization. To overcome this a **compensating winding** *C* is added. This winding, which, like the commutating pole winding, is in series with the armature circuit, is embedded in slots in the pole faces of the machine. It is really a part of the commutating pole winding distributed over the entire polar and interpolar region and is so proportioned that it completely neutralizes the field produced by the armature. As it has no definite magnetic circuit, saturation does not impair its efficiency with excessive over load. It effectively prevents all shifting of the field and consequently insures sparkless commutation at all times. It is used on most heavy duty motors. Fig. 485 shows a section of the field structure and windings of such a machine.

The armature for one of these machines is pictured in Fig. 486 and the complete motor is shown in Fig. 487.

This rolling mill drive is really a special application of the old Ward-Leonard system of control, devised by Mr. Leonard originally for the operation of variable speed elevators, and later used for coal hoists, ammunition hoists on shipboard, for street cars, locomotives and a number of other purposes, where smooth acceleration, great flexibility and high efficiency were required.

SECTION X — CHAPTER VII

DIRECT-CURRENT MOTORS

REVERSING MILL MOTORS

1. Outline the apparatus involved in the heavy-duty reversing-mill motor equipment.

2. Explain in detail the complete cycle of operation of the reversing-mill motor equipment. Sketch general connections.

SECTION XI CHAPTER I

ELECTRIC ELEVATORS

GENERAL PRINCIPLES

There are two general types of electric elevators.

1. The drum type.
2. The traction type.

The first electric elevator was installed in Baltimore in 1887. It had a worm gear and was of the drum type. It was operated by a series wound motor connected to a constant current circuit. This was followed in 1889 by the installation of two electric elevators of the drum type with compound wound motors in New York City. They were decidedly successful and other installations followed rapidly.

The general scheme of the drum type elevator is shown in Fig. 488. Here the car C is suspended by two or more sets of

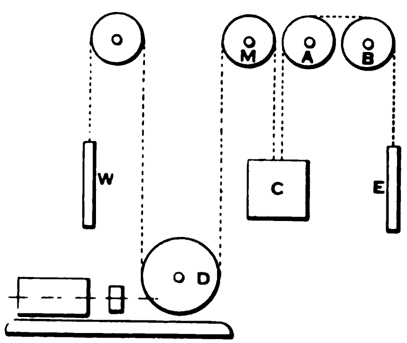


FIG. 488.

cables, one of which passes over the main sheave M and is anchored on a hoisting drum D. Attached to the same drum, is another cable which is attached connected to a counter weight, W, called the back drum counter balance. Another set of cables extends over a separate set of sheaves, A-B, to an independent counter balance E. The drum must be of sufficient diameter and length to accommodate in one layer, the cable, which raises the car. When the car is at the bottom of its travel, the drum is covered by the cable attached to the back drum counter

balance. As the car rises this cable unwinds from the drum and the cable raising the car replaces it on the drum. This type elevator is not suited for very high buildings on account of the excessive size of drum that is required and it is rarely used for speeds greater than about 350 feet per minute. The two counter weights combined are generally equal to the weight of the car plus one-half of its maximum load. This insures that with the average load the car will be exactly counter balanced, and the power required to rotate the drum will be that required to overcome friction losses only. The hoisting drum is p.ovided with a gear operated by a worm drive attached to the shaft of an electric motor. A single worm is employed on small machines but for heavy-duty high-powered machines two worm-driven gears rotating in opposite directions are arranged to divide the strain.

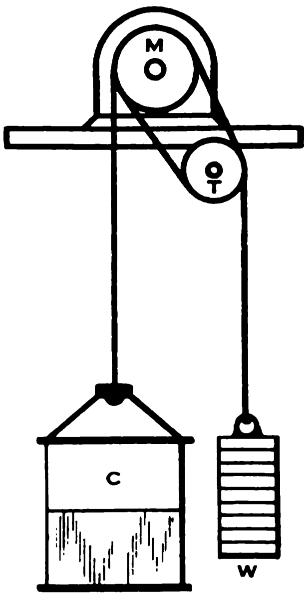


FIG. 489.—Simple arrangement of rope gearing for traction elevator.

The traction type of elevator made its appearance in 1905 and is being used almost exclusively for long travel, high-speed work. The mechanical construction is exceedingly simple, consisting of a slow-speed motor directly connected to a driving sheave, below which is placed an idler sheave. Fig. 489 shows the arrangement. The car *C* hangs on one end of the cable and the counter weight *W* on the other. The cable passes over the pulley *M* of the motor and thence over the idler *T*, and then again over a second groove on the motor pulley and thence to the counter weight. The motor pulley is about 3 feet in diameter, and has sufficient surface contact with the cable to insure that it will not slip.

The traction elevator has an advantage over the drum type machine in that the ropes are always in a vertical position and there is no danger of the car over running at the top or bottom of the shaft. If the motor should continue to revolve after the

car has reached the end of its upward travel, the counter weight having reached the end of its downward travel, rests upon a buffer and the cable would therefore slacken and allow the motor to revolve without any further movement of the car.

This type of elevator requires a motor of very slow speed,

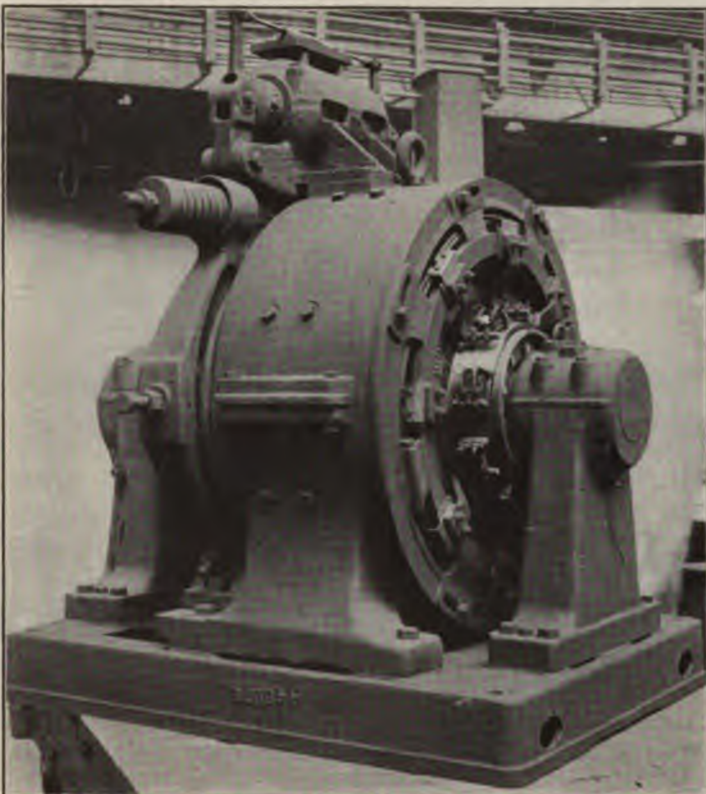


FIG. 490.—Small slow-speed traction elevator type of motor with electro-magnetically released brake manufactured by the Westinghouse Electric and Manufacturing Company.

about 60 r.p.m. for a vertical rise of 600 feet per minute with a pulley approximately 3 feet in diameter.

The motor for a certain elevator of this type is rated at 35 horse power, but because of the extremely low speed it weighs 21,000 pounds.

Fig. 490 illustrates a Westinghouse motor of this type for traction elevators with electro-magnetically released brake.

For speeds of 400 feet or less a geared type of traction elevator is preferable. This permits the use of a motor of higher speed which will weigh and cost correspondingly less. It is possible to largely avoid the disadvantages of the gear drive by using an arrangement of sheaves giving a two to one ratio without gears. This requires the placing of an additional idler sheave on the car and another on the counter weight, shown at *A* and *B*, in Fig. 491. For a car traveling at the same speed as

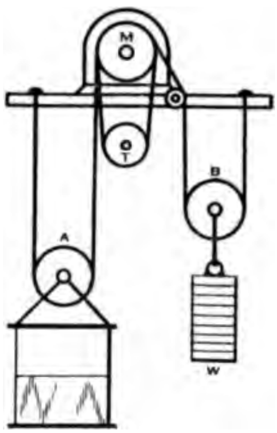


Fig. 491.—Scheme for obtaining two to one ratio of gearing with ropes for traction elevator.

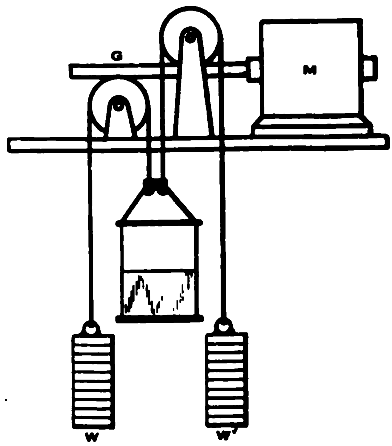


Fig. 492.—Double worm drive for traction elevators, permitting a greater reduction in size of driving motors.

the one in Fig. 489, the motor *M* could travel twice as fast and develop the same horse power with a machine of approximately half the weight, for the speed of the car is one-half the peripheral speed of the driving sheave on the motor. Where it is desired to further reduce the size of the motor the plan illustrated in Fig. 492 may be employed. This involves a worm drive similar to the drum type of elevator except that the traction principle is employed, for there is no hoisting drum. The motor. *M*, attached to the shaft *G*, carries worm gears, and drives two sheaves at right angles thereto. The car is supported by two counter weights and any desired ratio of gearing may be secured.

A still simpler form of traction elevator eliminates one of the gears and one of the counter weights illustrated in Fig. 492.

A substantial form of traction elevator with A. C. induction motor and worm drive, built by The Ohio Elevator Company for automatic operation through push-button control, is shown in Fig. 493.

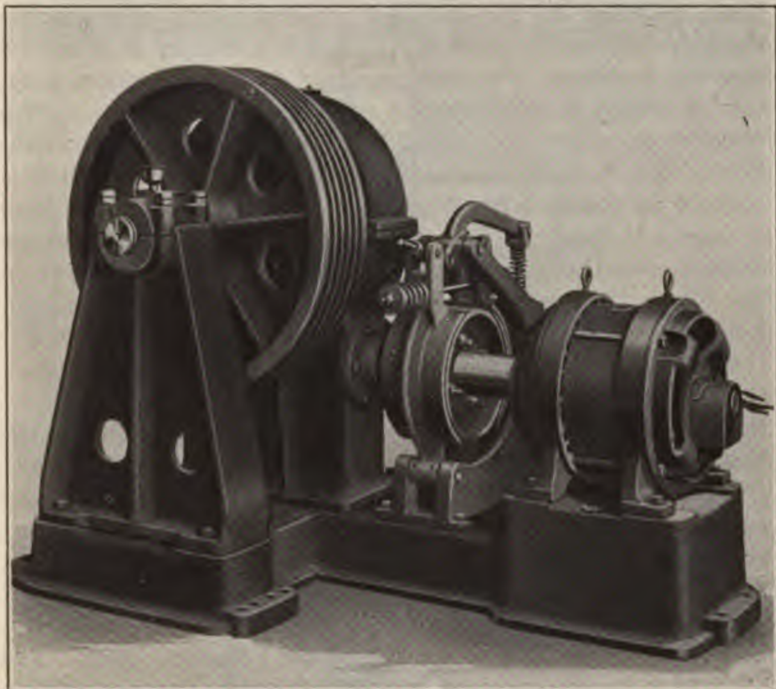


Fig. 493.—Traction elevator machine with "V" grooves on main sheave. Induction motor drive through worm gears. Electro-magnetically released brake. Built by The Ohio Elevator Company.

SECTION XI CHAPTER I

ELECTRIC ELEVATORS

GENERAL PRINCIPLES

1. Explain the general principle of the drum type electric elevator.
2. Explain the general principle of the traction type of electric elevator.
3. Sketch and explain the method of obtaining a two-to-one ratio of gearing with ropes for traction elevator.
4. Explain the geared type of traction elevator. What are its advantages?

ELECTRIC ELEVATORS

METHODS OF CONTROL

Elevators may be controlled by means of a handle, wheel or lever, attached to the car and communicating mechanically through a rope with a switch attached to a shipper drum on the hoisting machine. The movement of this drum closes a reversing switch in one direction or the other depending on the direction in which it is desired to move the car. The acceleration of the motor following the closing of the main switch is entirely automatic. An elementary diagram for a simple form of starter is shown in Fig. 494. The movement of the shipper drum throws the reversing switch B into the position shown in the figure. Current from the mains is then admitted simultaneously to the brake release magnet, C, the shunt field, D, and the armature, A, in series with a starting resistance, R. Before the admission of current, a powerful spring sets a band brake on the coupling between the motor and the worm drive of the hoisting machine. This brake is sufficiently powerful to hold the car in any position. When the switch is closed admitting current to the motor armature and field, the brake coil is energized and exerts an upward pull of several hundred pounds, sufficient to release the brake. Current in the armature now develops enough torque to hold the car. Assuming the load to be within the capacity of the motor, the armature starts. The solenoid E, being connected in shunt with the armature, will not be energized before the armature starts as the low resistance of the armature virtually constitutes a short circuit around the solenoid. As the armature rises in speed, however, its counter e.m.f. added to the ohmic drop, produces sufficient potential difference at the terminals of the solenoid to cause it to raise its core. The rapidity of this rise may be checked if necessary by a dash pot. The resistance R is gradually cut out and the motor automatically accelerated to full speed. The reversing switch B is opened by the mechanical attachment from the car in order to stop. The solenoid core drops to its original position reinserting resistance in the armature circuit, while the brake coil

is de-energized and the spring sets the brake on the motor coupling. Operating the shipper drum in the reverse direction throws the reverse switch into the dotted position. This reverses the current in the armature while maintaining the current in the field in the same direction as at first. The reversal of the current in the brake-release coil is incidental to the connections and is of no consequence.

A simple form of electrical control is shown in Fig. 495. Here a solenoidal magnet, *A*, is arranged to lift the plates *B* and *C*

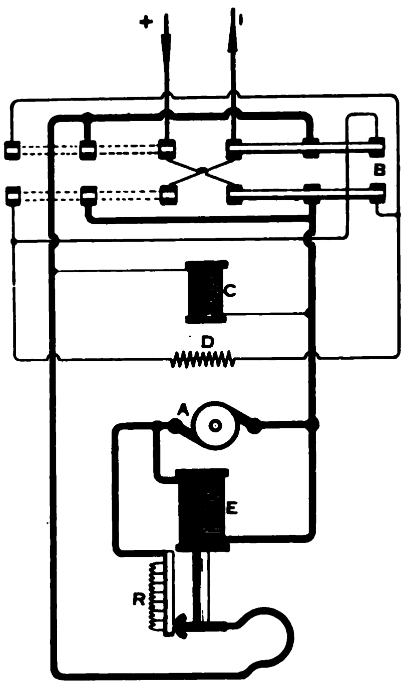


FIG. 494.—Simple circuits for magnetically controlled electrically operated automatic motor accelerator for electric elevators.

into the dotted position, while magnet *D* similarly raises plates *E* and *F*. When the car switch, *G*, is closed as shown, coil *A* is thrown across the line by a circuit which may readily be traced. If it were possible to throw the switch suddenly into the dotted position and close the circuit on *D*, the line would be short circuited provided the plates *B* and *C* stuck and failed to return

to their normal position. To guard against this, an electrical interlock is provided. The circuit through *A* is completed via the bottom contacts under plate *F* which can only be closed provided switch *D* has released plates *E* and *F* and they have returned to their normal position. Likewise the circuit for *D* is completed through the lower contacts of the plate *C*. It is impossible, therefore, for one of these switches to be closed unless the other switch has positively opened its upper contacts. In

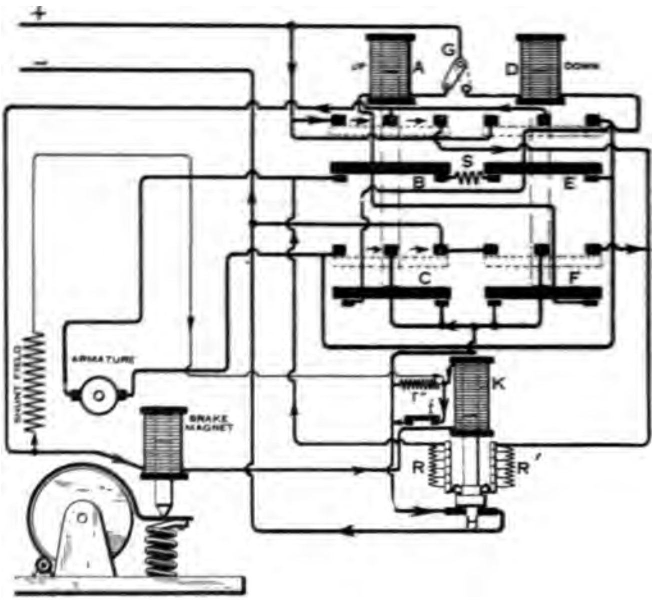


FIG. 495. Simple form of electrical control for automatic acceleration of electric elevator motor.

addition this current must pass through another electrical interlock provided in the control circuit at the point *H* before it can energize *U* or *D*. If the core of the solenoid, *K*, which cuts out the armature resistance, should stick at its uppermost or any intermediate position when the car switch is off, plate *C* having returned to its lowest position, the control circuit would be open at the point *H*, thus preventing throwing the armature across the line without the resistance *R* and *R'* being in series therewith.

When *B* and *C* rise, current is admitted to the shunt field,

brake release magnet and solenoid in series, and the armature in series with the starting resistance R and R'. An adjustable dash pot governs the rate at which the solenoid cuts out the starting resistance. The final movement of the core of the solenoid in an upward direction separates the plate f from the contacts beneath it, inserting the resistance r'' in series with the shunt field, brake release magnet and solenoid. This resistance lowers the field strength and gives the highest notch of speed. At the same time the current is reduced in the brake release magnet, and solenoid, to the amount necessary to retain them in the highest position. Throwing the car switch G into the dotted position reverses the current in the armature, and the acceleration in the reverse direction takes place as before.

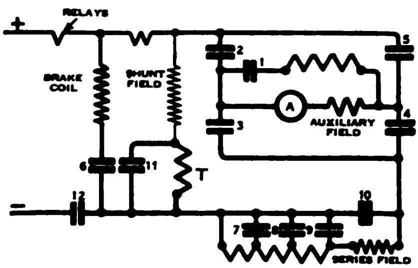


FIG. 496.—Power circuits for electric elevator using electro-magnetic switches for producing proper combinations during acceleration.

When the core of the solenoid rises the contacts at H are opened. The control circuit is therefore broken at this point, but it had been previously closed via another route when the plate C reached its upper position.

High-speed passenger elevators always employ magnet switches throughout, to control the acceleration. Fig. 496 shows the power circuit for a passenger elevator with the 12 unit-switches necessary. The master controller on the car is usually moved promptly from "off" to full "on" position. The switches then operate automatically under the control of relays to start the motor and accelerate it promptly and smoothly to full speed. Fig. 497 shows the order in which the switches are operated. In starting switches 3, 5, 6, 11 and 12 close. This gives the motor full field strength with the starting resistance in the armature circuit.

After the motor is started switch 1 closes for a brief period. Then switch 1 opens, and the armature resistance is cut out in three steps by switches 7, 8 and 9. Finally the series field is short-circuited by switch 10 and a resistance is cut into the shunt field by opening switch 11. The series turns on the field have a tendency to smooth out the peaks in the current curve while the starting resistance is being cut out when these field turns are short-circuited, by the operation of switches 9 and 10. This prevents sudden changes of field magnetism, so that the speed continues to accelerate smoothly when the field weakening resistance, T, is inserted in a single step. The master switch may

SW	RUN UP							OFF							RUN DOWN						
	3	2				1		BRAKE			O	BRAKE			1		2				3
1						O		O	O	O		O	O	O		O					
2															O	O	O	O	O	O	O
3	O	O	O	O	O	O	O														
4															O	O	O	O	O	O	O
5	O	O	O	O	O	O	O														
6	O	O	O	O	O	O	O	O	O				O	O	O	O	O	O	O	O	O
7	O	O	O	O	O												O	O	O	O	O
8	O	O	O	O				O	O				O	O				O	O	O	O
9	O	O	O						O				O						O	O	O
10	O	O								O		O								O	O
11		O	O	O	O	O	O	O	O	O		O	O	O	O	O	O	O	O	O	
12	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O

FIG. 497.—Sequence of operation of switches shown in Fig. 496. The operation of these switches in the order stated is determined by a control circuit not shown.

be held on the second point if desired, which produces about one-half maximum speed. The first point is the "slow-down" speed for making a landing. The usual practice is to move the handle to the first point, giving the motor full field strength and inserting resistance both in series and in shunt with the armature. This produces about one-fourth the maximum speed. Moving the handle to the "off" position opens all control switches and applies dynamic braking, which, combined with the mechanical brake, brings the car smoothly to rest.

The operating circuit for a traction type of elevator is shown in Fig. 498. The power is directed through the medium of interlocking relays and unit switches through the shunt field,

brake release coils, armature, etc. The motor armature is controlled by a main switch and two contactors of the reversing switch. This arrangement also disconnects the armature starting resistance, the series brake coil and the series field winding from both sides of the line in the "off" position of the controller. In this position the shunt field is partially energized, for the field maintaining resistance is in the circuit although the field weakening switch is closed. The advantage of maintaining the field

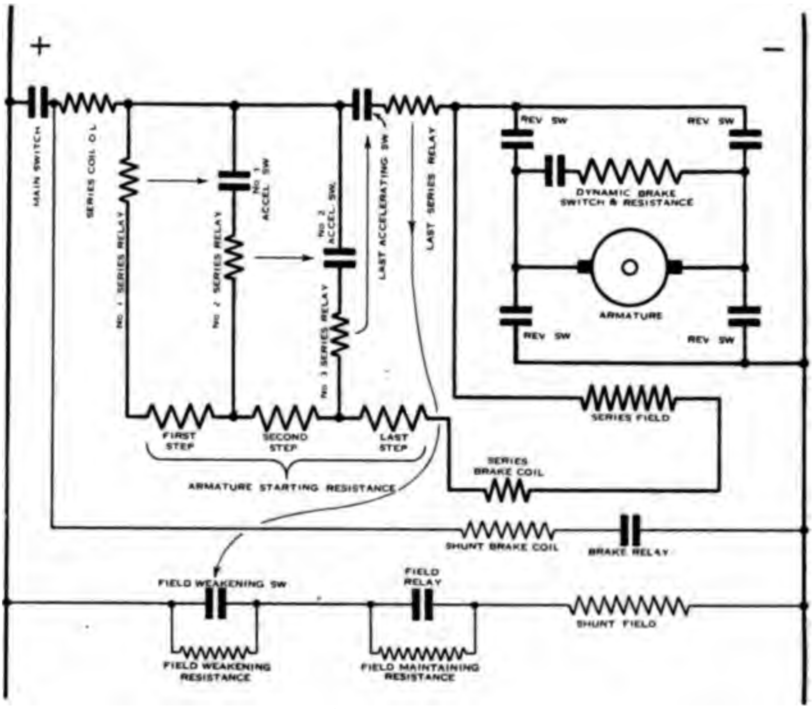


FIG. 498.—Power circuit for traction type of electric elevator.

at partial strength is to insure a quick start, otherwise the hysteresis would involve a considerable time lag. When the main reversing switch and the dynamic brake switches are closed, the motor operates at slow speed. The field strength is then a maximum, for the field weakening switch and field relay are closed. The coil of the dynamic brake switch is connected to the motor armature so that this circuit is kept closed in stopping until the motor comes practically to rest.

The braking effect of the current in this circuit is always available to assist the mechanical brake.

It is not possible to stop high speed elevators smoothly with mechanical brakes alone without excessive coasting. Furthermore the amount of coast will vary with the load. If the brakes are set to stop the elevator with a given amount of coast with light load, the car would coast too far with heavy load. The energy stored in a moving body is proportional to the square of the velocity. A mechanical brake can only absorb energy in direct proportion to the velocity, but the dynamic brake will dissipate energy proportional to the square of the velocity. A judicious combination of the two will insure that the car will stop with practically the same amount of coast regardless of the load. The mechanical brake is relied upon to hold the car at a landing but the most effective part of the stopping is due to the dynamic brake.

The mechanical brake is normally set to hold the car by means of a powerful spring or weight. The magnet for releasing the brake, in its latest form, embodies both a series and a shunt winding. The shunt winding is not sufficient to release the brake but will hold it when once released. The series winding, aiding the shunt, will raise the brake. This arrangement reduces the size of the brake magnet and at the same time gives an interlock which prevents the brake from being released unless it is assured that there will be current in the motor armature circuit.

The motor is accelerated through the medium of four series relays. When the main switch is closed current passes through three sections of the starting resistance, the series brake coil, series field, reversing switches and motor armature, to the negative side of the line. Should the armature circuit be opened no current could flow through the series brake coil. Although the shunt brake coil is energized, this alone will not release the brake. Therefore the car cannot be released in case the armature fails to receive current. When the car is running, and the series field coil is short-circuited, the series brake coil is included in this circuit and is deprived of line current. This does not permit the resetting of the brake as the shunt coil is able to hold it in the released position.

Relay number 1 controls the cutting out of the first step of starting resistance. When the counter e.m.f. reduces the

current in this relay so that its armature will fall, it is made to connect the first accelerating switch across the line. At the same time it inserts relay number 2. When the counter e.m.f. reduces the current sufficiently in this relay, its armature falls and energizes accelerating switch number 2 and inserts relay number 3. When relay number 3 falls it energizes the last accelerating switch and the last series relay. When the armature current lowers to the proper value, the operation of the last series relay opens the field weakening switch and therefore increases the speed of the motor from normal to maximum. Here, as in the preceding scheme illustrated in Fig. 483, it is found possible to cut the field weakening resistance into the circuit at one step and obtain a perfectly smooth acceleration, because the series field winding is on a closed circuit and the lowering of the main field flux is resisted by the reaction of the currents induced in this circuit. The field weakening switch is designed to allow an arc to form momentarily as the switch opens, which assists in reducing the field current gradually.

Push Button Control

The automatic or push button control type of elevator is designed for small slow speed passenger service in private houses or apartments. It is intended to be operated at velocities not greater than 150 feet vertically per minute and the car is generally only 3 or 4 feet square and designed to carry a light load of from two to four people.

The hoisting machine is of the drum type similar to that used where there is an elevator attendant. The car is controlled, however, by push buttons and requires no attendant. To obtain control of the car, a button beside the door opening on the hatchway is pushed. If the car is not in use, it starts from wherever it may be, and proceeds to the particular floor where the button was pushed and stops. Then, and not before, the door is automatically unlocked and may be opened by the person awaiting the car. Entering the car, the passenger must close and latch the door before the car can be started. This done, he pushes one of a set of buttons in the car, numbered to correspond to the various floors. The car immediately starts and proceeds to that floor, where it stops. The door may then be opened. After leaving the car the door is closed, either by the passenger

or automatically. Then, and not before, another person may secure control of the car. Fig. 499 is an elementary diagram of connections for this type of elevator control. m_1, m_2 and m_3 are magnetic relay switches of which there is one for each elevator landing. *Nm* is a non-interference magnet which prevents "stealing" the car by another person, when someone is using it. Buttons f_1, f_2, and f_3 are placed beside the hatchway doors on each floor. The car contains a duplicate set of these buttons connected through a flexible cable in multiple with the ones shown. s_1, s_2 and s_3 are door switches attached to the locks of

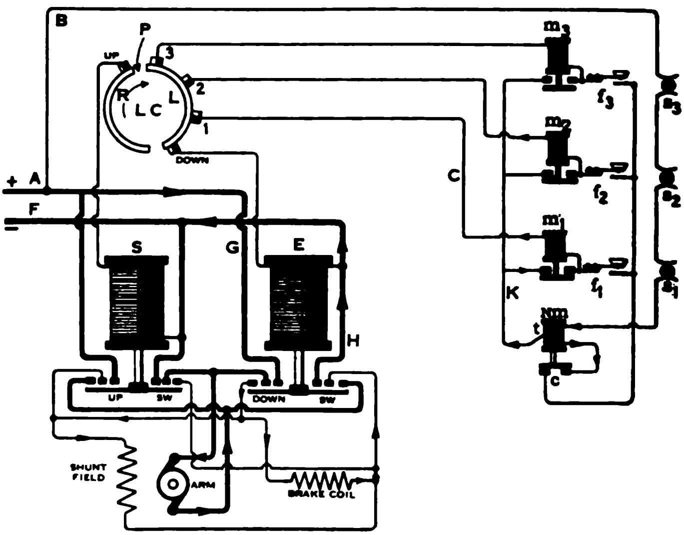


FIG. 499.—Control circuits and simple power circuits for automatic push button type of electric elevator.

each hatchway door and are so arranged as to open the control circuit unless all of the doors are closed and locked. *LC* is a landing controller which governs the direction of the car and insures that it will stop at the proper floor. It consists of a large wheel containing two metallic half segments, electrically insulated from each other. This wheel is geared to the hoisting machine and arranged to make not quite one-half of a complete revolution while the car travels from the top to the bottom of the hatchway. On the circumference of this wheel, and placed diametrically opposite to one another, upon the two segments,

are two brushes, "Up" and "Down," which connect to the directional switches controlling the direction of the car. Spaced around one of these segments are brushes 1, 2 and 3, connecting to the floor relays. In the position of the landing controller shown, the car is at the top of the hatchway. If the button f_1

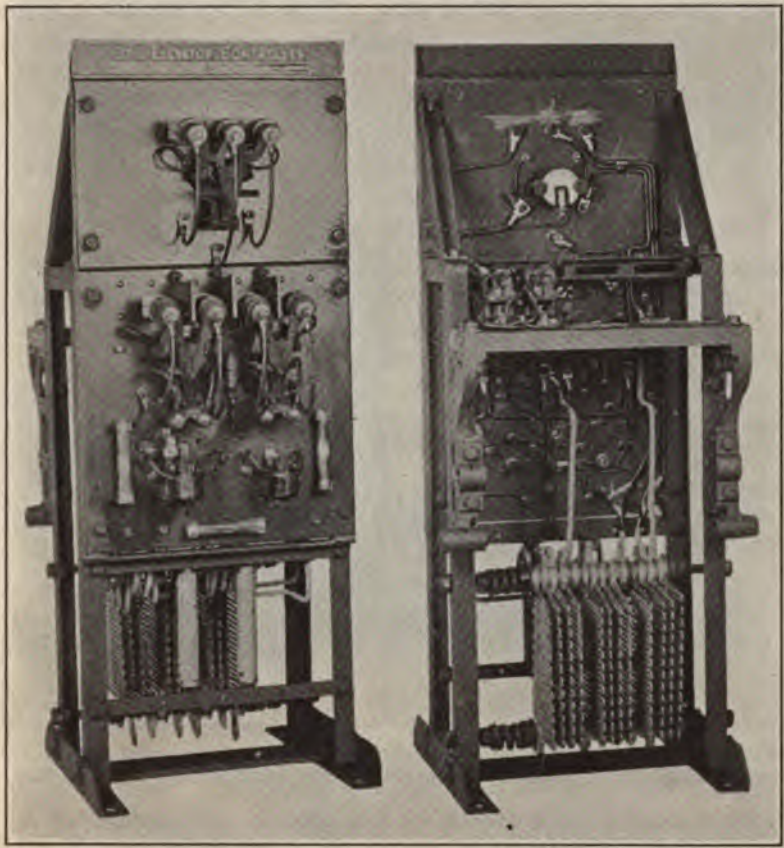


FIG. 500.—Front and back views of control panel for Otis automatic electric elevator.

is pressed to bring the car to the first floor, current enters over the line A, thence via the control circuit B, through the door switches, thence through the noninterference magnet Nm and through the lower contacts c, of this switch. Thence it passes via f_1 and energizing coil of m_1 via wire C to brush 1 of the landing controller, thence through the "Down" brush to magnet E and

out to the negative side of the line, F. The "Down" switch closes and current is admitted over the power circuit wires G-H to the armature shunt field and brake coil of the hoisting machine. The starting resistance and details of the accelerating circuit are omitted. The noninterference magnet Nm has a dashpot which insures its moving slowly. This gives time for m_1 to close first after which the core of Nm rises. When m_1 closes the current that was previously passing through the contacts c, now finds a

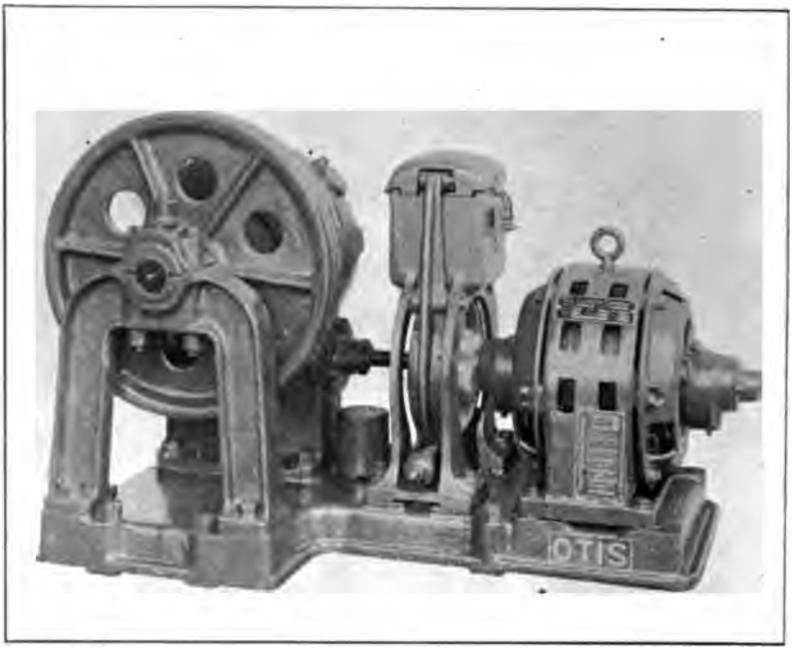


FIG. 501. Traction type hoisting machine with electric brake and A. C. induction motor for automatic electric elevator, built by the Otis Company.

way through a tap t, thence via the wire K and contacts of m_1 through wire C to the landing controller. This current does two things: In the first place it holds m_1 closed so that the path through f_1 is no longer necessary. Thus when f_1 is released m_1 does not drop open. Second, the contacts at c having been broken, it is impossible to control the car by closing f_2 or f_3, that is, the noninterference magnet prevents the operation of the car from any of the other push buttons. The motor lowers the car and as it does so the segment L moves in the direction of the

arrow, first breaking contact with brush 3 and then with brush 2. When the gap P comes between brush 1 and the "Down" brush, the control circuit over the wire C to the magnet E is broken. The switch E drops open, the power is shut off the motor, and the mechanical brake is applied. The position of brushes 1, 2 and 3 are adjustable on the circumference of the landing controller so that the proper amount of coast may be allowed to bring the car to a rest at the exact floor level. When the car stops at the first floor the dash pot on Nm is then so adjusted as to allow a time interval of about five seconds during which the door may be opened before the contacts at c close. This prevents any one else getting control of the car during the time elapsing between the stopping of the car and the opening of the door. Let it be supposed that the car is to be raised to the third floor. Pushing the button in the car in multiple with f_3, switch m_3 is energized, the non-interference magnet Nm interrupts the control circuit for all of the buttons and the control current is led into brush 3 on the landing controller. This brush is now in contact through the segment R with the "Up" brush of the controller, which admits current to the "Up" switch, S. When this closes, current is admitted to the shunt field of the motor and brake coil as before and to the armature in the reverse direction. The car then moves up instead of down. Fig. 500 represents a control panel with the various switches required for this type of elevator. Fig. 501 shows the appearance of the hoisting machine and motor.

SECTION XI CHAPTER II

ELECTRIC ELEVATORS

METHODS OF CONTROL

1. Explain the principle of mechanical control for an electric elevator. What are its advantages and disadvantages? For what kind of elevator is it adapted?

2. Explain the principle of electrical control in its simplest form for electric elevators. What are its advantages and disadvantages?

3. Explain the general principle of electrical control by means of a number of shunt-connected magnetic switches.

4. Sketch the power circuits for an electric elevator, using magnetic switches for acceleration.

5. Tabulate in their proper order the switches which must be actuated by the controller for producing acceleration to full speed of the above-mentioned motor.

6. Explain the construction of the mechanical brake and the method of releasing the same.

7. Explain the principle of dynamic braking and how it is applied.

8. Which of the two forms of braking should be employed on an elevator and why?

9. Explain the general scheme of the shunt, current-limit type of accelerator for traction elevator motors in connection with series relays.

10. Explain the general plan of the automatic or push button type of electric elevator. How is the car stopped at the desired floor? How is interference with the control prevented after the car has been once started?

SECTION XII CHAPTER I

FACTORY TESTING OF GENERATORS AND MOTORS

TESTING OF MOTORS

All of the large manufacturers of generators and motors maintain testing departments where tests are performed upon their machines. As has already been pointed out, the commercial efficiency of a machine is the ratio of its output to its input. Thus, if a motor receives one horse power, that is, 746 watts, at its terminals, and delivers ¾ of this amount at its pulley, its efficiency is 75%.

A little consideration will show why it is so important to know what the efficiency of a generator or motor actually is. Suppose a company manufactures a 500-kilowatt generator, having an efficiency of 95%. Another company manufactures a machine of the same rated output but with an efficiency of 90%. The loss in the first machine is 5% of 500 kilowatts or 25 kilowatts. The loss in the second machine is 10% of 500 kilowatts or 50 kilowatts. The second machine continually wastes 25 kilowatts more than the first machine. Assume that these generators are to be operated for 10 hours per day, 365 days per year. A fair estimate of the cost of power in a steam plant is 1½ cents per kilowatt hour. Take the 25 kilowatts excess power wasted, in the second machine over the first. Multiply that by 10 hours per day 365 days per year, and that by 1½ cents per kilowatt hour, and the value of this power is found to be $1,368. This represents the additional cost of power required to operate the second machine over and above what would be required for the first. As $1,368 represents the interest on a very considerable investment, the 500-kilowatt machine with an efficiency of 95% would be worth a much higher purchase price because of the economy of its operation.

There are two methods of testing the commercial efficiency of electric motors:

1. The dynamometer method.
2. The electrical or stray power method.

The dynamometer method involves the use of some form of absorption dynamometer, which is applied to the pulley and

serves to absorb the power developed by the motor at the same time that it is made to indicate the torque, which is one of the factors of the motor's output. A convenient form of dynamometer for this purpose, especially adapted for small motors, is the "**Prony Brake.**" The apparatus for this test consists of a special, double-flanged pulley of relatively large diameter, hollow inside

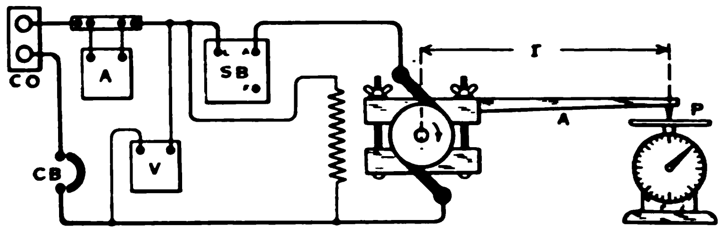


FIG. 502.—Wiring connections for motor with Prony brake attached for measuring output.

and with a thin circumference. The pulley is made hollow in order that the heat generated by friction upon its surface may be readily transmitted to the water therein. Surrounding the pulley is an adjustable clamp arranged like a brake, as shown in Fig. 502. Extending from this clamp is a brake arm, *A*, near the end of which is a point, *P*, which rests on a pair of scales or balances. The motor is wired to a source of supply through a starting box with voltmeter and ammeter in the circuit. After the motor is started, the brake band or clamps are tightened to load the motor. As the motor reacts under the load, it takes power from the line which is indicated on the electrical measuring instruments. A speed counter is employed to count the r.p.m. The torque which the motor develops in pound-feet is the product of the radius *r*, of the brake arm, *A*, in feet, and the pounds indicated on the scales. If the radius of the brake arm is one foot, then the scales indicate the torque directly in pound-feet. The weight of the brake arm must be deducted from the number of pounds registered on the spring scales to determine the exact torque. To do this the Prony brake should be placed on a knife edge, as shown in Fig.

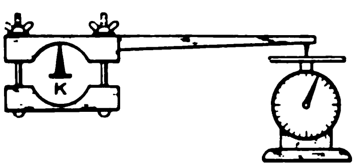


FIG. 503.—Method for balancing Prony brake on knife edge to determine "tare."

503. When so placed, the amount indicated on the scales should be deducted from the actual scale reading. This amount is called the **tare** of the brake. This is a direct method of measurement. The input is shown on the measuring instruments and the output obtained from the product of the speed and pound-feet torque. The ratio of the output to the input is the commercial efficiency of the motor.

An illustration will show the application of this method. Consider a motor loaded as shown in the figure until it takes its full rated current of 55 amperes and 125 volts or 6,875 watts. Let the radius of the brake arm be one foot and assume that the spring scales register 43.7 pounds and that the tare is 2 pounds. Deducting the tare leaves 41.7 pounds net. The speed as counted at full load is 1,000 r.p.m. Applying first the formula for the horse power developed

$$H.P. = \frac{nT}{5252} = \frac{1000 \times 41.7}{5252} = 7.94 \text{ horse power output.}$$

Dividing the input, 6,875 watts, by 746 watts per horse power, gives 9.21 horse power. The commercial efficiency then is

$$\frac{7.94 \text{ output}}{9.21 \text{ input}} \times 100 = 86.2\%.$$

The electrical or stray power method is an indirect method of measuring the efficiency of a motor. First the input under load is measured. Second, all of the losses in the motor are carefully measured by electrical means. These losses are then deducted from the input. The remainder is the output. The output may then be divided by the input and the commercial efficiency ascertained. This method is more accurate than the dynamometer method because all of the measurements are made by electrical instruments which are capable of greater accuracy than an absorbtion dynamometer.

Four measurements are necessary. First, the input to the machine under load. Assuming the same motor as above, the intake at full load will be 55 amperes and 125 volts, as in Fig. 504. The output may be absorbed by causing the motor to drive a generator which in turn is loaded back into the supply line or other resistance, or the motor may be loaded upon a brake or other dynamometer. The amount of this output is not measured. The motor is simply loaded until it takes its rated input.

The second measurement will be to ascertain the field losses. Connections are shown in Fig. 505. The machine is shut down and the armature disconnected. The current is passed through the field winding at line potential, an ammeter being in series and a voltmeter in shunt therewith. Under these conditions the

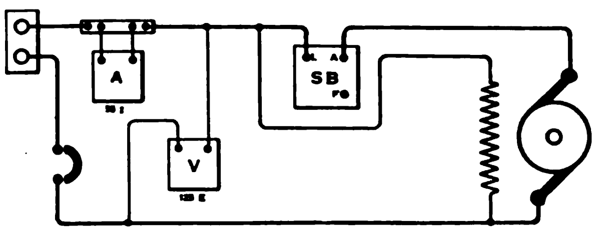


FIG. 504.—Diagram of connections for measuring input to motor to check speed at rated input.

field current is 2 amperes and the line potential 125 volts. Two amperes multiplied by 125 volts equals 250 watts field loss.

After the motor has run for a sufficient time to insure that its field and armature windings are thoroughly heated to full load working temperature, it is shut down and the field is disconnected. A current is passed through the armature from a source of sup-

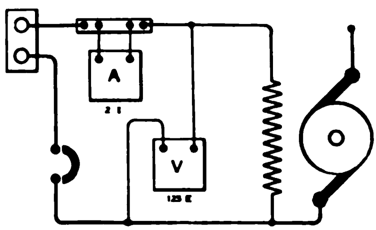


FIG. 505.—Diagram of connections for measuring field loss in motor.

ply, said current being adjusted by means of a water rheostat as shown in Fig. 506. An ammeter indicates the current and a voltmeter the drop across the brushes. The current employed at this time should not exceed full load current and yet should be sufficient to produce a readable drop on the voltmeter. The resistance of the armature is calculated by dividing the voltage drop by the current in the armature. This measurement includes not only the resistance of the armature winding but the resistance of the brushes, the contact resistance between the

brushes and the commutator, the resistance of the leads between the brushes and terminals of the machine and the resistance of the commutating pole windings, if the machine has them. These form a part of the armature circuit and the losses therein should be included in this measurement. In this case it will be assumed that the full load armature current is employed. If the motor's intake is 55 amperes and the field intake is 2 amperes,

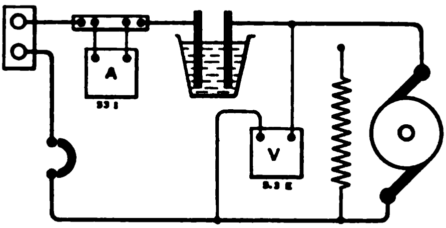


FIG. 506.—Diagram of connections for measuring resistance of motor armature preliminary to determining armature copper loss.

then the armature gets the difference or 53 amperes. Let the drop in potential across the armature with this current be 5.3 volts.

$$\frac{E}{I} = R = \frac{5.3}{53} = 0.1 \text{ ohm, resistance of armature circuit.}$$

It is customary to take three sets of readings with the armature in different positions, observing the current and corresponding potential drop in each case. The average resistance of the three sets of measurements is taken as the true resistance of the armature circuit. Care should be taken not to allow the motor to run without load before measuring the armature resistance, as the circulation of air, thereby induced, will cool it off and lower its resistance. The resistance of an armature under normal working temperature may be from 12 to 20% higher than the same armature at room temperature.

The copper loss in the armature circuit is, according to the preceding readings, I^2R and 53 amperes squared multiplied by 0.1 ohm equals 280.9 watts, armature loss.

The fourth measurement is to ascertain the **stray power.** This includes all losses in the motor, not included in the two preceding measurements. These losses are due to eddy currents, hysteresis, bearing friction, brush friction and windage. Con-

nections are shown in Fig. 507. The field is energized at line potential to full strength. A water rheostat is inserted in series with the armature for the purpose of lowering the voltage at the brushes until the speed falls from the somewhat higher no load speed to the normal speed at which the motor would run when fully loaded. The current in the armature and the potential

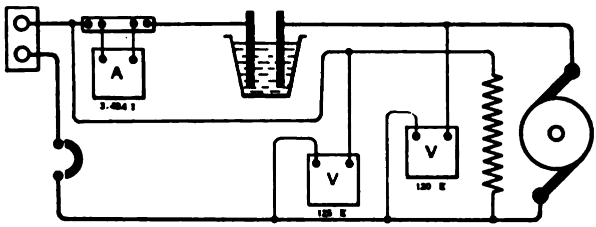


FIG. 507.—Diagram of connections for measuring stray power in motor.

across the brushes will now be observed. Assuming these to be as shown, the stray power loss will be 3.484 amperes multiplied by 120 volts equals 418.1 watts.

Tabulating:

Armature intake, $I \times E = 55 \times 125 =$		6,875
Field loss, $I \times E = 2 \times 125 =$	250.0	
Armature loss, $I^2R = 53^2 \times 0.1 =$	280.9	
Stray power, $I \times E = 3.484 \times 120 =$	418.1	949
Delivered power, in watts =		5,926

$$\frac{5926 \text{ output}}{6875 \text{ input}} \times 100 = 86.2\% \text{ commercial efficiency.}$$

The reason that the motor should be fully heated to its working temperature when the above tests are made is because the field current decreases as the resistance of the field winding increases on account of the rise in temperature, thereby changing both the r.p.m. and the field I^2R loss. The field loss varies as the square of the current but directly with the resistance.

If the actual efficiency of the motor alone is wanted the no-voltage release coil in the starting box should not be in series with the field winding, as its resistance reduces the current in the field and increases the speed of the motor. In small machines this winding sometimes has a resistance of 10% of that of the field winding.

SECTION XII CHAPTER II

FACTORY TESTING OF GENERATORS AND MOTORS

TESTING OF GENERATORS

The efficiency of a generator may be obtained by the electrical or stray power method. The measurements are similar to those involved in the testing of a motor by the same process.

The generator is operated under normal conditions of speed and voltage at full load. Since the speed is usually a fixed value and the load is a definite amount, the object of this load test is to determine the field current necessary to produce normal terminal voltage at normal speed at full load. If the efficiency is to be determined at several points, this test is repeated for those load values. The field current is usually increased with the load, due to increased IR drop and increased armature reaction, requiring more field current to produce normal voltage at the terminals.

The resistance of the armature is taken by the voltmeter-ammeter method as soon as the machine is shut down. (The machine must not be allowed to run without load before taking this resistance test as it will tend to reduce the heat by fanning itself cool.) A low reading voltmeter is used and the current is some convenient value (not exceeding full load current) which will give a good deflection on the voltmeter. This reading is repeated three times, turning the armature in three positions to allow for errors in brush contact, etc. The mean of these three readings is taken as the true value unless one is evidently erratic, in which case the readings are repeated. If the machine has commutating poles, the resistance of the windings on these poles is taken at this time. It should be noted that the resistance of the armature as found includes the resistance of the brushes and brush leads and the contact resistance of the brushes which is correct as the running resistance is wanted. This is not the same as the resistance of the armature as used in temperature test in which case the resistance of the armature alone is taken.

The generator is then connected to operate as a motor, the direction of rotation being the same as before. The armature

has applied to its terminals the voltage **generated** at each of the desired steps for which the efficiency is to be ascertained. This generated voltage is found by multiplying the armature current (load amperes plus the field amperes if the generator was self excited) by the resistance of the armature (plus the resistance of the commutating pole winding if used) and adding the voltage drop thus obtained to the terminal voltage. This drop varies with the load and must be computed for each step taken. For greatest accuracy this voltage must be increased by the drop in the armature of the machine when running as a motor. The current upon which this drop depends must be determined by trial by applying approximately the correct voltage at the terminals with the machine operating as a motor and multiplying the current by the armature resistance.

The reason for applying the **generated** voltage in the stray power test is as follows:

The friction and windage are determined by the speed in a given machine.

The iron losses are determined by the speed and the flux. The flux varies with different loads due to different requirements of generated voltage and is modified by the armature reaction.

When running the generator as a motor, the same conditions of speed and flux must be present. The speed can be determined and adjusted.

Under any condition, the generated voltage is proportional to the flux, as,

$$E_g = \frac{\Phi z n}{10^8}.$$

When operating as a motor, the counter voltage is:

$$E_c = \frac{\Phi z n}{10^8}.$$

As the machine is without load the counter voltage may be assumed to be equal to the impressed unless the refinement mentioned before is desired. Assuming that the impressed voltage $E_i = E_c$ and that z is the same in both cases, 10^8 being of course constant:

$$E_g = E_c = E_i$$

and E_i is proportional to the flux, Φ, times the speed, n. That

is, in both cases, motor and generator, the product of flux and speed must be constant. Then if the generated voltage be applied to the machine as a motor and the flux in the field adjusted so as to give the same speed, the correct values of flux and speed are present and the armature will absorb just enough power to overcome this loss plus a small I^2R loss which may easily be calculated.

The armature copper loss is found for each step by multiplying the armature current (load amperes plus field amperes) squared by the resistance of the armature. The I^2R loss of the commutating winding may be included or calculated separately by the same method.

The field loss is found by multiplying the field amperes by the terminal voltage for each step. This includes the loss in the field rheostat which is correct, as the rheostat is necessary to control the voltage and is properly a part of the machine.

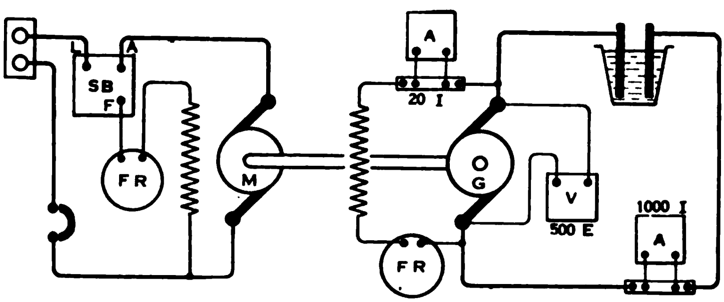


FIG. 508.—Diagram of connections for measuring load upon generator and field loss.

The stray power is found by multiplying the current in the armature in the stray power test by the applied voltage.

A preferable method of determining the stray power loss is to first construct an iron loss curve and also take the friction and windage losses which will be constant for a given speed. To find the stray power loss for any load, the watts iron loss for the required generated volts are found and added that to the constant friction and windage loss for the complete stray power loss. This also eliminates the small I^2R loss mentioned in the above note.

As an example, let it be assumed that a generator of 500

kilowatts rated capacity, 1,000 amperes at 500 volts, is driven at its rated speed by a motor and connected to an external circuit which will absorb its full rated output, Fig. 508. Under these conditions let the field current be 20 amperes at 500 volts. This is somewhat greater than the field current would be at light load

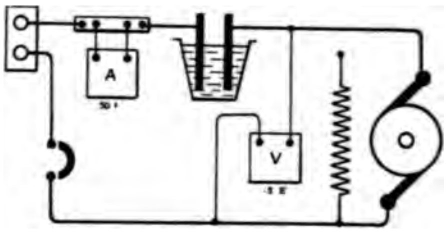


FIG. 509.—Diagram of connections for measuring armature resistance of generator preliminary to calculating armature copper loss.

on account of armature reaction, and IR loss in armature. The field loss will be 20 amperes times 500 volts or 10,000 watts.

Let the machine be now shut down and the armature resistance measured as in Fig. 509. Assume the current to be 50 amperes and the drop obtained 0.5 volt.

$$\frac{E}{I} = R; \qquad \frac{0.5}{50} = 0.01 \text{ ohm armature resistance.}$$

This is assumed to be the average of the three separate sets of readings with the armature heated. The current in the armature will be 1,000 amperes load current plus 20 amperes field current or 1,020 amperes total. The armature loss will be found from;

$$I^2R = P: \qquad 1{,}020^2 \times 0.01 = 10{,}404 \text{ watts armature loss.}$$

Now let the machine be run as a motor in the same direction as that in which it was driven as a generator, the connections being as shown in Fig. 510. A rheostat, however, must be inserted in the field circuit and another in the armature circuit. An ammeter is connected to show the intake for the armature, while the voltmeter shows the potential drop across it. The two rheostats WR and FR must be adjusted until two conditions obtain. First, the voltage on the voltmeter V must be equal to that which the armature actually produced as a generator. This

is equal to the terminal voltage, 500, plus the IR drop in the armature. 1,020 multiplied by 0.01 equals 10.2 volts, armature drop. 500 volts delivered plus 10.2 volts loss equals 510.2 volts generated.

Second, the speed must be adjusted, until the machine runs as a motor at the same speed as that at which it was driven under full load as a generator. Assuming the armature under these conditions to take 10 amperes, the stray power will be 10 amperes multiplied by 510.2 volts equals 5,102 watts loss in stray power.

It will be observed that this stray power measurement includes some copper loss which was included in the preceding measure-

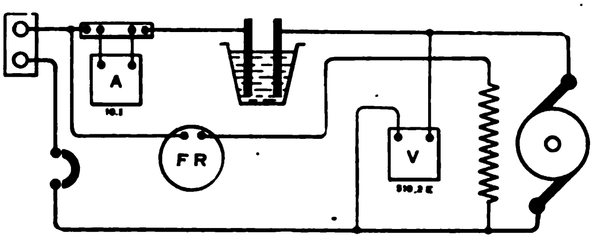


FIG. 510.—Diagram of connections for measuring stray power of generator.

ment. The amount of this loss, I^2R, is very small. Thus 10 amperes squared, multiplied by 0.01 ohm armature resistance equals 1 watt. It is evident that the included copper loss is so small that it may be neglected.

Tabulating:

Field loss..................	10,000 watts.
Armature loss..............	10,404 watts.
Stray power................	5,102 watts.
Total loss................	25,506 watts.

The generator absorbs its output 500,000 watts, plus all the losses, 25,506 watts or 525,506 watts. It generates its output 500,000 watts, plus the armature loss, 10,404 watts, plus the field loss, 10,000 watts, or 520,404 watts.

$$\frac{500{,}000 \text{ output}}{520{,}404 \text{ generated}} \times 100 = 96\% \text{ electrical efficiency.}$$

$$\frac{500{,}000 \text{ output}}{525{,}506 \text{ intake}} \times 100 = 95.15\% \text{ commercial efficiency.}$$

SECTION XII — CHAPTERS I AND II

FACTORY TESTING OF GENERATORS AND MOTORS

TESTING OF MOTORS

1. A motor absorbs 16 amperes at 220 volts. A prony brake arm with a radius of 1 foot pulls 20 pounds on the scales at 1,080 r.p.m. What is the commercial efficiency of the motor?

2. A motor absorbs 28 amperes at 120 volts. A prony brake arm with a radius of 1 foot pulls 32 pounds on the scales at 650 r.p.m. What is the commercial efficiency of the motor?

3. Explain the method of measuring the armature loss in a generator or motor. Sketch connections and give illustration.

4. Explain the method of measuring the field loss in a generator or motor. Sketch connections and give illustration.

5. Explain the method of measuring the stray power in a motor. Sketch connections. What operating conditions must be met and why?

6. Explain the method of measuring stray power in a generator. Sketch connections. What operating conditions must be met and why?

7. Having measured the losses in a motor, explain how the efficiency may be computed without measuring either the output or the input. Give formula.

8. Having measured the losses in a generator, explain how the efficiency would be determined without measuring either the output or the input.

9. A generator delivers a current of 100 amperes at a pressure of 220 volts. Its field resistance is 22 ohms; its armature resistance is .05 ohm. When tested for stray power, the armature absorbs 10 amperes. Determine: (*a*) The stray power in watts; (*b*) the field loss in watts; (*c*) the armature loss in watts; (*d*) the commercial efficiency at full load.

10. A 220-volt 50-ampere motor runs 1,000 r.p.m. Its armature resistance is 0.1 of an ohm; its field resistance is 44 ohms. When running at full speed with no load, its armature absorbs 5 amperes. Determine: (*a*) The stray power in watts; (*b*) the commercial efficiency.

FACTORY TESTING OF GENERATORS AND MOTORS

FIELD SATURATION AND IRON LOSS CURVES

Fig. 511 shows the connections for taking the data from which to construct the **field saturation curve** of a generator. Here a motor-generator set is designed to run at constant speed. The volts generated in the armature at different excitations are plotted against the current in amperes in the generator field. In a test of a small 2 kilowatt machine the data under **generator** in the following table were obtained.

Motor				Generator	
Volts	Armature amperes	Armature watts	Speed	Field amperes	Generated volts
228	1.30	296.4	1880	0.00	8 (residual)
228	1.35	307.8	1880	0.10	86
228	1.40	319.1	1880	0.15	130
228	1.50	342.0	1880	0.20	160
228	1.55	353.4	1880	0.25	188
228	1.60	364.8	1880	0.30	208
228	1.80	410.4	1880	0.40	240

From this data, the curve, Fig. 512, was constructed. The first point on the curve indicates the residual voltage generated without any current in the field. When the field excitation is increased, the voltage rises and the curve gradually bends over as saturation approaches. This curve is really a permeability curve of the iron or steel structure constituting the field frame. It shows the quality of the iron or steel of the field frame's magnetic circuit and the degree of saturation to which it is worked.

An iron loss curve shows the watts absorbed by the motor to supply the losses due to eddy currents and hysteresis in the armature of the generator at different degrees of saturation.

The data may be taken at the same time with the data for the field saturation curve. It is shown under **motor** in the preceding table. When there is no load on the armature of the generator

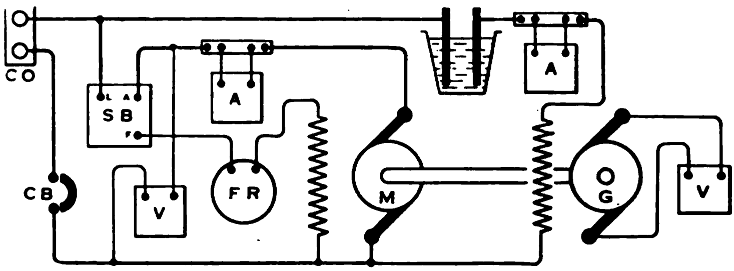


Fig. 511.—Diagram of connections for securing data upon which to construct field saturation and iron loss curves for generator.

and when its field circuit is open, the input to the motor from the line is simply the power required to supply the windage and friction losses in the two machines and the eddy current and

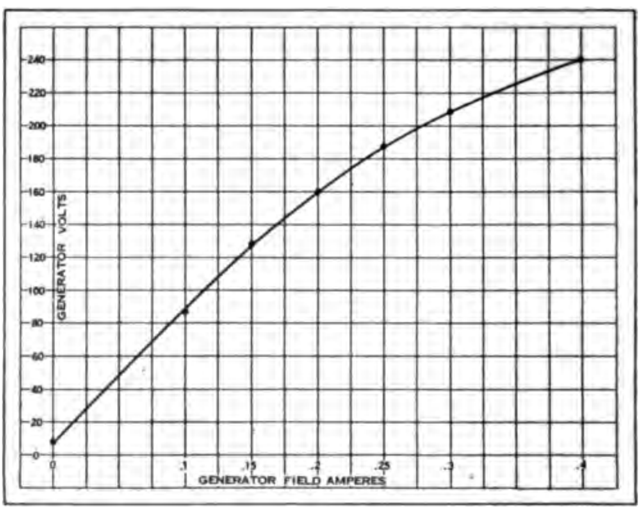


Fig. 512.—Field saturation or open circuit characteristic curve of generator.

hysteresis loss in the motor armature. In the 2-kilowatt motor generator set referred to, this input was 1.3 amperes at 228 volts, which is 296.4 watts.

Now when the field of the generator is excited, more power will be required to drive it. This increase in power demanded by the motor to drive the generator, when its field is **fully** excited in excess of the amount required to drive the generator **without** field excitation, is an **exact measure** of the **power required** to supply the **eddy current** and **hysteresis losses** in the **generator.** The particular loss at any instant depends upon the degree of excitation of the generator. The higher the excitation the greater the loss. As the current is increased in the generator field and the resulting voltage rises, it will be observed that the input to

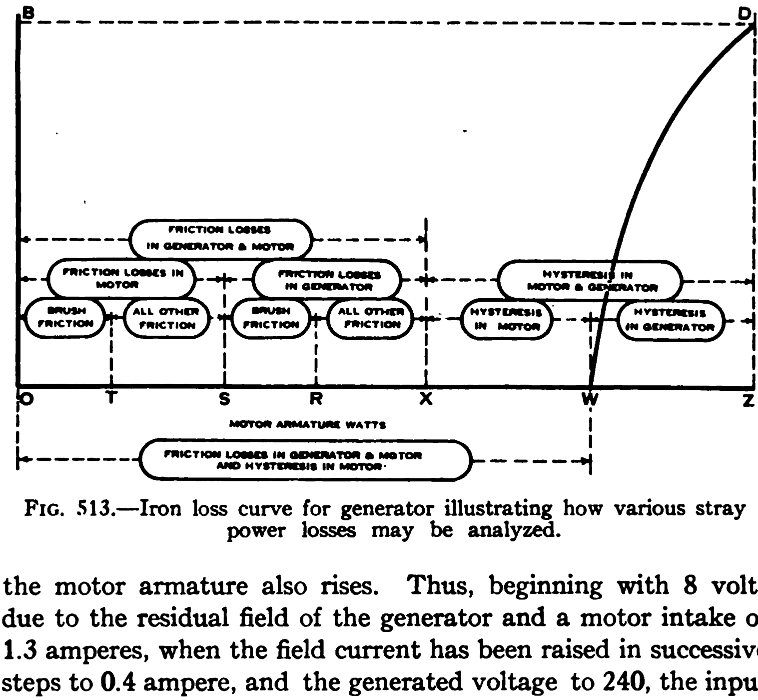


FIG. 513.—Iron loss curve for generator illustrating how various stray power losses may be analyzed.

the motor armature also rises. Thus, beginning with 8 volts due to the residual field of the generator and a motor intake of 1.3 amperes, when the field current has been raised in successive steps to 0.4 ampere, and the generated voltage to 240, the input to the motor has increased to 1.8·amperes or 410.4 watts. From this data the iron loss curve may be constructed. This is shown in Fig. 513. Here the generated volts are plotted against the motor armature watts. The first point of this curve was obtained by laying off on a horizontal line, *O-W*, 296.4 watts input, when the field of the generator was not excited. As the excitation of the field was gradually increased, the generated volt-

age rose to O-B, while the input to the motor armature increased from O-W, 296.4 watts, to the extent of W-Z, 114 watts, making a total O-Z, 410.4 watts. Thus the curve W-D is obtained.

For greater accuracy, the increased I^2R loss in the motor must be deducted from the iron loss watts. This is because the increased current taken by the motor causes an increased loss in the copper of the motor armature, which is not justly chargeable to the generator.

If the hysteresis and eddy currents in the generator, W-Z, amount to 114 watts, the motor and generator being duplicates of each other, it may be assumed that an equal amount of power was consumed by hysteresis and eddy currents in the motor. Reckoning this 114 watts back from W will give a point X; thus X-Z will represent the hysteresis and eddy current losses in both motor and generator.

As the eddy current loss is very small, this may be practically considered all hysteresis loss provided the field poles are also laminated. Deducting the 114 watts hysteresis loss in the motor, W-X, from the friction losses in generator and motor and hysteresis in motor, O-W, leaves 182 watts friction losses in generator and motor, O-X. As the machines are duplicates, this may be divided in half, assigning 91 watts to friction losses in generator, and 91 watts to friction losses in motor. These losses may again be divided by a measurement of the brush friction. To obtain this, the set was run without load on the generator but with the brushes on the commutator. The input into the motor was 1.2 amperes at 228 volts, which is 273.5 watts. Carefully observing the input to the motor armature, the brushes were then lifted from the generator's commutator. This relieved the motor of a load equal to the generator brush friction. The motor promptly reduced its intake to 1.05 amperes at 228 volts or 239.4 watts. Subtracting the latter from the former gives 34 watts which is the brush friction for the generator. Separating this from 91 watts total friction loss, S-X, gives R-X, or 57 watts for bearing friction and windage. Assuming the brush friction to be the same in the motor it may be deducted from O-S, leaving T-S for bearing friction and windage in that machine. Thus, in Fig. 513, a graphic analysis of the stray power in motor and generator can be ascertained. A study may then be made of these losses and if they appear to

the designing engineer to be excessive, steps may be taken to reduce them.

Loading Back Tests

Small generators may be tested for efficiency, by loading them upon lamps or other resistance. Difficulty is experienced, however, in finding a load which will conveniently absorb the output of large machines. Furthermore, the power required to operate large machines under full load conditions would prove very costly. Both of these difficulties are overcome in the **Loading Back Test.** This test was designed by Hopkinson in England. It is best adapted for testing duplicate machines which are alike in all particulars. It is a very economical and convenient method. The general scheme consists in connecting the two machines upon the same shaft, one operating as a motor and one as a generator. The motor supplies power through its shaft mechanically to drive the generator. The generator supplies electrical energy through a circuit to drive the motor. Each machine falls short of being able to furnish the required power to drive the other, under full load, by the amount of losses therein. Assume two duplicate machines of 500 kilowatts capacity each, thus coupled. Let the efficiency of each be 95%. The losses in each machine would thus be 5% of 500 kilowatts or 25 kilowatts. The motor thus lacks 25 kilowatts of sufficient power to drive the generator, but is able to supply it with 475 kilowatts. The generator lacks 25 kilowatts of being able to drive the motor, but is able to supply it with 475 kilowatts. If, now, the sum of these two sets of losses, or 50 kilowatts, be supplied from some external source, the motor with this outside assistance would be able to drive the generator and the generator with the outside assistance would be able to drive the motor and both machines would operate under full load and a total of 1,000 kilowatts would be circulating. The two machines could thus be tested under full load conditions while the total energy wasted would be merely the 50 kilowatts supplied from without.

There are three schemes for supplying these losses. In the **Kapp test,** the losses are supplied **electrically** from a separate source in **shunt** with the generator of the set. In the **Hopkinson test** the losses are supplied **mechanically** by means of a **separate driving motor** connected to the motor-generator set under test, which thereby aids in driving the set. In the **Potier test,** the

losses are supplied **electrically** by means of a **separate source** in **series** with the generator of the set being **tested.**

Loading back tests are commonly **designated as the Hopkinson tests** because Hopkinson conceived the **scheme of loading** the motor upon the generator and then loading **the generator back** upon the motor, but the plan of supplying **these losses electrically** from a source in shunt with the generator is **due to Kapp.**

Kapp Test

The connections for the Kapp test are shown **in Fig. 514.** The fields of both generator and motor are **supplied from the separate** source *L-L*, through rheostat *F-R*, ammeters **being in series and** voltmeters in shunt therewith to indicate the **power absorbed** in these circuits. The armature of the motor is **supplied from** the

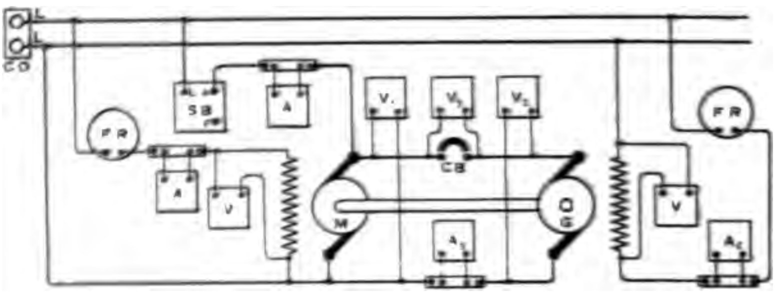


Fig. 514. Diagram of connections for Kapp **loading back test.**

auxiliary source through starting box *S-B* and **ammeter** A_1. An additional circuit is provided between the motor and generator which includes an ammeter A_3 to show **the circulating current** and a circuit breaker *C-B* with a voltmeter V_3 **across** its terminals.

A voltmeter V_1 is placed across the motor **armature** and another V_2 across the generator armature. **With the set standing** still and disconnected from the line, the **first** step in the loading back test is to energize the field of the motor to full strength and admit current through the starting box gradually to the armature of the motor. The set comes up to speed, after which the field of the generator is excited. **The voltage** of the generator is shown on V_2, which should be equal and opposite to the counter e.m.f. of the motor shown on V_1. This may be insured by a proper adjustment of the generator's field strength. Under these conditions voltmeter V_3 should read **zero.** Should the generator's field be excited in the wrong direction, the e.m.fs.

of the motor and generator would be thrown in series instead of in opposition. Under these conditions voltmeter V_3 would show twice the voltage of one machine. If this happens, the field of the generator should be reversed. It should be then adjusted until V_2 shows a voltage slightly higher than V_1. The excess will be indicated by V_3. The circuit breaker *C-B* should then be closed. This will be followed by a small current circulating between the motor and generator which will be registered on A_3. The amount of power circulating may now be increased by increasing the excitation of the generator's field. As the current from the generator flows through the motor armature, it reacts at the same time through the generator shaft upon the motor and calls for more power mechanically. As the motor reacts under this load it calls for more current, which is supplied by the generator. If the generator's field will not admit of a sufficient increase in strength to circulate the entire output of power required, as might be the case when the field rheostat was all cut out, a still further increase in circulating current may be obtained by weakening the field of the motor. When the rated output of the generator is reached, the two machines may be continuously operated under full load conditions as long as may be desired. This method of testing overloads the motor armature to the extent of the combined losses of both machines with the exception of the two field losses, and therefore unequal heating and possibly different efficiencies may result. In the test upon the 2-kilowatt set referred to, the data in the following table were obtained while loading back:

Motor

Speed	Field volts drop	Field current	Line volts	External current	Total armature current
1880	145	0 3	224	3.5	11.5

Generator

Circulating current	Voltage of circulating current	Field current	Field volts drop
8	225	0.4	224

The data from the loading back test may now be used for the purpose of calculating the efficiency of each of the two machines.

The generator is loaded to its rated capacity, but as the motor has to supply the losses in both motor and generator (with the exception of the two fields) its armature has to absorb these losses in addition to the rated output of the generator. This overloads the motor in this particular case nearly 50%. Nevertheless the efficiency of the two machines came out about the same. The calculations are as follows:

Generator

Watts delivered	$= 8 \times 225$	=	1,800
Field loss	$= 0.4 \times 224$	= 89.6	
Armature loss	$= 8^2 \times 1.6$	= 102.4	
Stray power	$= \dfrac{410\,(\text{G and M})}{2}$	= 205.0	
	Total loss =		297

Power absorbed by generator = 2,197 watts

$$\frac{1800 \text{ delivered}}{2197 \text{ absorbed}} \times 100 = 82\% \text{ efficiency.}$$

Motor

The motor supplies all the watts absorbed by the generator except generator field.

Power absorbed by generator		= 2197	
Power absorbed by generator field		= 90	
Motor delivers.		=	2,107
Field loss	$= 0.3 \times 145$	= 43.5	
Armature loss	$= 11.5^2 \times 1.6$	= 211.6	
Stray power	$= \dfrac{410\,(\text{G and M})}{2}$	= 205.0	
	Total loss =		460

Power absorbed by motor = 2,567 watts.

$$\frac{2107 \text{ delivered}}{2567 \text{ absorbed}} \times 100 = 82\% \text{ efficiency.}$$

The armature's resistance was obtained by taking separate sets of readings on the two machines with different currents in each case and averaging the result.

Because of the unequal load on the two machines involved in the test just described, it is customary to load the generator back into the line and make separate tests on the motor and generator, each being fully loaded during the period it is under test.

SECTION XII CHAPTER III

FACTORY TESTING OF GENERATORS AND MOTORS

FIELD SATURATION AND IRON LOSS CURVES

1. Explain the method of obtaining the field saturation curve of a generator. What does this curve indicate? Sketch connections. Draw a sample curve.
2. Explain the method of determining the iron loss in a generator. What does this indicate? Sketch connections. Draw a sample curve.
3. What is the object of the "loading back" test?
4. What is the difference between the Kapp, Hopkinson and Potier "loading back" tests?
5. Sketch connections for performing the Kapp "loading back" test.
6. Give a detailed explanation of the various steps involved in performing the Kapp "loading back" test.

SECTION XIII CHAPTER I

DESIGN OF DIRECT-CURRENT MACHINES

FUNDAMENTAL PRINCIPLES

The design of dynamos is the result of the application of certain fundamental formulas combined with the results of long experience based on a multitude of experiments.

An electric generator may be considered as a mass of steel and a mass of copper. The object of the steel is to furnish a path for the magnetic flux. The mass of copper provides a path for the electric currents. There are thus two elements in a generator: **Flux capacity** and **Current capacity.** These factors form the foundation of the machine. The basis for the generation of electrical energy in a dynamo-electric machine is the total flux passing the air gap between field and armature. This flux is cut during rotation by a belt of electrical conductors occupying the surface of the armature. The flux capacity of the machine is proportional to the air gap area, which in turn is measured by the circumference of the armature multiplied by the length of the armature core. If D represents the armature diameter and L its length, the total flux is then proportional to D times L.

The flux capacity for a given area of air gap is not the same in all machines, yet for a given type it is fairly well fixed. In general, the flux capacity of any machine will increase directly with the diameter of the armature and directly with the length of the core. These dimensions of the armature may also be taken to represent the area of the air gap. Therefore any changes in the design of the machine which either increase or decrease the area of the air gap, will affect the flux capacity in a corresponding manner. The steel of the field structure through which the flux path is completed is incidental. It is simply employed to make the air gap flux possible.

The conductors on the armature surface may be considered as having a definite cross-sectional area. The total area is equal to the cross-section of all the copper in one slot multiplied by the number of slots. This total area of copper may be considered as one wire which will give a measure of the ampere-conductor capacity, that is, the current which the total number

of conductors would be capable of carrying when connected in parallel. If this cylindrical belt be considered as one large wire, then the total current carried would represent the ampere-conductor capacity of the winding. Thus, if the armature contained 100 conductors, each conductor carrying 5 amperes, the total ampere-conductor capacity when the wires were all connected in parallel would be 500 ampere-conductors. The ampere-conductor capacity is solely dependent upon the total cross-section of the copper. Therefore if all of the other factors are fixed, the cross section of copper will increase in direct proportion to the diameter of the armature, but it is independent of the armature length. That is, the ampere-conductor capacity is proportional to the armature diameter only.

As the flux capacity is proportional to the area of the air gap and as the ampere-conductor capacity is proportional to the area of the total copper, these two factors form the basis of the capacity of any electrical generator.

For a given amount of copper, the ampere capacity will depend on how well the conductors are ventilated. Therefore, for a given temperature rise, the better the ventilation the more amperes can be carried by a given cross-section of copper. This means that good design will necessitate a well ventilated armature. With a given ventilation and a fixed diameter of armature, and a given cross-section of armature wire, the total ampere-conductor capacity is fixed. That is, if all of the wires on the armature are united to form a single conductor, there is a sufficient cross-section of copper to carry a definite number of amperes, but if these conductors are so connected as to use half of them to carry the current back along the armature surface and the other half to carry the current forward on the armature, the number of effective conductors will have doubled but the current carried will be halved, yet the product of the amperes and conductors remains constant. Thus, an armature of fixed proportions may deliver 500 amperes from 1 conductor or 1 ampere from 500 conductors.

. Next consider the relation of these three factors, **flux, amperes** and **conductors,** with respect to each other. As the flux capacity is fixed, for a given size armature, and the ampere-conductor capacity is fixed, their product, which is a factor of the output of the machine, is also fixed. The amperes can be reduced

and the number of conductors increased by properly connecting the conductors on the armature.

When the armature is rotated, the voltage generated will depend upon the flux, the speed, and the number of conductors connected in series. The output is dependent upon the product of the volts and amperes. Therefore, the output must be proportional to **flux, speed, conductors** and **amperes.** These four factors may be varied through a great range and it is this variation that admits of the many different ratings which are obtainable from a given amount of steel and copper.

$$W = \Phi \times S \times Z \times I \times K.$$

In the above equation the watts output, W, equals the flux, Φ, times the speed, S, times the number of conductors, Z, times the amperes, I, times a constant, K. A consideration of this formula

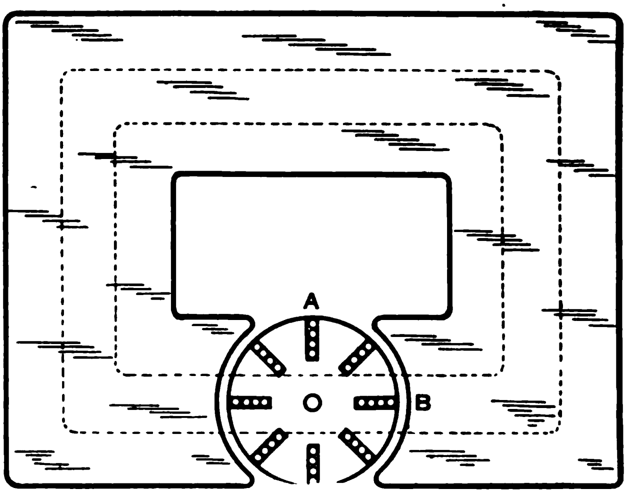


Fig. 515.

will emphasize a number of facts. Observe that a maximum flux and a maximum number of ampere-conductors must be employed if a maximum output is to be obtained, from an armature of given dimensions. But there is a limited space available for the flux, and the conductors on an armature of given size. It is not necessary that an armature of fixed dimensions and rated for a given output shall always carry the same flux, but if that flux is fixed the ampere-conductors will also be fixed, and while these factors may be altered, the alteration of one necessitates

changing the other. That is, if the flux is increased the ampere-conductors must be decreased and vice versa. Therefore an armature of given diameter and length may be designed to carry a large amount of flux and a small number of ampere-conductors or it may be arranged to carry a small amount of flux and a large number of ampere-conductors. The former conditions are illustrated in Fig. 515. This machine involves a large amount of steel and a small amount of copper. Such a machine is relatively heavy. It would, however, be efficient in operation. The other machine involves a large amount of copper and a

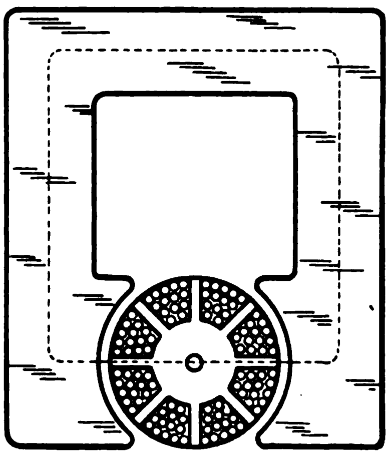


Fig. 516.

small amount of steel. This construction is illustrated in Fig. 516 and would be relatively lighter in weight. Its efficiency, however, in operating, would be lower than the preceding machine. One may be regarded as a steel machine because steel predominates, the other as a copper machine because copper predominates. For a given kilowatt output, it is thus possible to get the desired result from two machines totally different in design.

As the flux enters the armature perpendicular to the wires it might be supposed that the output of the armature could be increased by using very narrow and deep slots instead of having them wide and shallow. This is true to a limited extent. Good practice requires that the slots be made comparatively deep but the ultimate depth is restricted by other considerations. Deep

slots involve more self-induction when the current reverses in the conductors than is the case with shallow slots. This is because the conductors in deep slots are largely surrounded by iron, which results in high self-induction when the current in the conductors attempts to change, while the conductors in shallow slots have less iron in proximity thereto and consequently there is less e.m.f. of self-induction. It is therefore permissible to use deep slots with slow-speed machines where the time permitted for the reversal of the current in the conductors during commutation is prolonged, while high-speed machines must necessarily employ relatively shallow slots if the reversal of the current in the conductors is to be effected without sparking in the relatively limited time that the coil is short-circuited by the brush. Furthermore the slow-speed machines require a large amount of copper to insure high efficiency in operation while the high-speed machines may be constructed with relatively less copper.

For the same field frame and armature dimensions a variety of outputs may be obtained, depending on the speed. Thus, if flux and conductors alone are considered there may be obtained from the same structure:

100 kilowatts at 100 r.p.m.
200 kilowatts at 200 r.p.m.
500 kilowatts at 500 r.p.m.

If the machine is designed to produce 100 volts at 100 r.p.m. and give 100 kilowatts, then at 200 r.p.m. it will give 200 volts and 200 kilowatts and at 500 r.p.m. it will give 500 volts and 500 kilowatts.

In practice there are electrical and mechanical limitations which prevent this principle being extended indefinitely.

The voltage generated in a given structure depends upon the flux, speed and conductors. If the speed is fixed, the number of conductors in series must be increased to increase the voltage. Now as the product of the amperes and conductors is a constant quantity for a given size armature, the number of conductors may be increased only by reducing the ampere capacity. Thus, the same frame may be used to produce:

100 volts × 1000 amperes = 100 kilowatts at 100 r.p.m., or
200 volts × 500 amperes = 100 kilowatts at 100 r.p.m.

In the latter case there are twice the number of conductors in series and therefore twice the voltage but the ampere capacity has been halved.

The above outlined facts may be emphasized by observing that the **capacity** of a given frame structure is proportional to the **speed,** while the **voltage** at a given **speed** is proportional to the **number of conductors connected in series** on an armature.

Next consider the effect of changing the current in the armature. If the total amperes required is large, a large number of paths through the winding will be needed. This will necessitate a large number of poles in the field. Thus, machines of large ampere capacity will naturally be multipolar. Machines having but a small ampere output, even though designed for high voltage, may be constructed with a fewer number of poles.

Increasing the length of an armature increases the flux capacity, as already pointed out, but it does not increase the ampere-conductor capacity for the ampere-conductors are not dependent upon the length of the electrical circuit at all; therefore the output of an armature is directly proportional to the simple length.

Increasing the diameter of an armature increases both the flux capacity and the ampere-conductor capacity. Thus, doubling the diameter will double the ability to carry flux. The circumference and consequently the number of slots and therefore the ampere-conductor capacity will likewise be doubled. This would quadruple the armature's capacity. Therefore the output of an armature increases directly with the square of the diameter.

Combining these two facts, the statement may be made that the **output of any armature is directly proportional to the square of its diameter multiplied by its length.**

The output in watts will therefore be $P = D^2 \times L \times r.p.m. \times$ *output factor*. The aim of the designer is toward obtaining a high **output factor** for a given diameter, length and speed. Good design will therefore result in a large output at a minimum cost. One of the essential factors contributing to this result will be good ventilation.

DESIGN OF DIRECT-CURRENT MACHINES

ARMATURE DESIGN

The development of the complete formula for the output of an armature will now be discussed. The meaning of the letters used in the following expressions are:

p = number of poles in field.
Φ = magnetic flux per pole.
s = revolutions per minute.
Z = total number of face conductors on armature.
m = number of paths for current through armature winding.
D = diameter of armature in inches.
L = length of armature in inches.
Bg = flux density in lines of force per square inch, in air gap.
i = current in amperes in one armature conductor.
I = total armature current.
K = ampere-conductors per inch of circumference.

The number of lines of force cut by each conductor on the armature per second is:

$$\frac{p\,\Phi\,s}{60}. \qquad (1)$$

If an armature revolves 60 revolutions per minute and the flux per pole is 500,000 and there are 2 poles in the field, then:

$\frac{2\times 500,000\times 60}{60}$ = 1,000,000 lines of force cut by each conductor in one revolution.

Thus, if in Fig. 502, 500,000 lines entered the armature from one pole and left at the other pole, a single conductor on the circumference would cut that flux twice or a total of one million lines in one revolution, which, as stated, would be accomplished in one second.

As it is necessary to cut 10^8 lines of force in one second to generate one volt, the average voltage generated in the above conductor will be:

$$\frac{p\,\Phi\,s}{10^8\times 60}. \qquad (2)$$

This is the **average** voltage because, when the conductor is at A, Fig. 502, it will generate no voltage and at B it will generate a maximum voltage. As the conductor varies in position in its rotation, the voltage obtained in the above expression will be neither the zero nor maximum, but the average.

If the armature winding has "m" paths connected in parallel, then the number of conductors in series in each path will be:

$$\frac{Z}{m}. \tag{3}$$

As the total voltage developed by the armature is the same as the voltage of one path, combining formulas 2 and 3 gives the total voltage, thus:

$$E = \frac{p\ \Phi\ s}{10^8 \times 60} \times \frac{Z}{m}. \quad (4) \qquad = \frac{p\ \Phi\ Z\ s}{10^8 \times 60 \times m}. \tag{5}$$

That is, the voltage developed in one conductor multiplied by the number of conductors in series in one path gives the total voltage generated in the armature winding.

The total armature current, I divides through "m" paths in the armature. If i represents the current per path then

$$I = m \times i. \tag{6}$$

The power in watts produced by the armature is equal to the generated voltage multiplied by the total armature current.

$$P = EI \quad (7) \qquad = \frac{p \times \Phi \times Z \times s}{10^8 \times 60 \times m} \times mi = \frac{p\ \Phi\ Z\ s\ i}{10^8 \times 60}. \tag{8}$$

Here the equivalent for the total voltage and the equivalent for the total current are multiplied together to get equation 8. This eliminates m, the number of paths. Now Zi equals the total ampere-conductors on the armature and $p\Phi$ equals the total magnetic flux from all the poles entering or leaving the armature. Therefore

$$P = \frac{\textit{total magnetic flux} \times \textit{total ampere-conductors} \times \textit{r.p.m.}}{10^8 \times 60}. \tag{9}$$

The total flux may be expressed another way as follows:

$$p\ \Phi = \%\ \pi\ D\ L\ Bg. \tag{10}$$

Where $\pi\ D\ L$ represents the total number of square inches on the cylindrical surface of the armature and $\%$ equals the per-

centage of the armature surface embraced by both pole pieces. Multiplying the product of these four factors by Bg, the number of lines of force per square inch in the gap space between the poles and the armature, gives the total flux $p\Phi$, in the machine. The total ampere-conductors on the armature surface are:

$$Zi = \pi K D. \tag{11}$$

Inserting the values thus obtained in equation 9, gives:

$$Watts = \frac{\% \pi D L Bg \pi D K}{10^8} \times \frac{s}{60}. \tag{12}$$

Simplifying the above gives the complete formula for watts generated:

$$Watts = \frac{\% \pi^2 D^2 L Bg K s}{10^8 \times 60} \tag{13}$$

This equation contains six unknown quantities. The watts desired are known and π is a constant. The variables are:

Per cent of armature circumference embraced by pole pieces.
Armature diameter.
Armature length.
Flux density in air gap.
Ampere-conductors per inch of circumference.
Revolutions per minute.

Only one of these can be calculated by the formula. The other five must be arbitrarily assigned. The skill of the designing engineer lies in his ability to assign suitable values to these various quantities.

The watts given in the above formula represent the power generated in the machine. The difference between that and the power delivered, is small, and may be neglected in machines of 50 kilowatts and upwards. The difference between the power delivered and the power generated is the amount of the electrical losses in field and armature.

$$\text{The electrical efficiency} = \frac{\text{Power delivered}}{\text{Power generated}}.$$

The electrical efficiency in machines of one kilowatt is about 80% and in machines of 500 to 1,000 kilowatts, 97½% to 98%.

The percentage of armature circumference embraced by the pole pieces should be as large as practical and yet leave a suitable gap for commutating purposes. If the percentage is small, the

flux emanating from the pole will be small. This would mean a small flux capacity and therefore a small output. If the percentage is too large, there will be leakage across the adjacent pole tips and too narrow a space to admit of commutation. As a definite time is required to reverse the current in a coil, a definite gap space is essential between adjacent pole tips. The field poles may cover from 60% to 80% of the armature circumference. The usual amount is 75%.

The diameter of the armature has an important bearing on the capacity of the machine. While all of the other variable factors affect the output in simple direct proportion, the watts delivered vary as the square of the armature's diameter. Sometimes this factor is determined by the equation, the others being assigned, but as the armature diameter has a direct bearing on two or three other factors, it is best to have it known or assumed. If the space available is fixed in advance, the diameter of the armature will be fixed. This is particularly so in the case of street car motors. As the diameter of street car wheels is usually about 33 inches, with a motor geared and hung upon one side of the axle, the diameter of the armature is restricted by the available space to the ground. As the car wheels have a fixed diameter established by practice and railway motors have been standardized as four-pole machines, the diameter of the armature is limited in advance to a fixed maximum.

The length of an armature for a drum winding is rarely more than 15 or 18 inches. This length gives the maximum permissible potential difference between adjacent commutator segments with a coil of but one turn, and two face conductors. With any greater length than this and with usual flux densities, the voltage will be so high that there is danger of flashing over between the adjacent segments upon which each coil must terminate. The inductance of a coil also increases with the length of the armature for the area of iron within the embrace of the coil is thereby increased and this in turn increases the field for the inductive operations of the coil. Self-induction opposes the reversal of the current in the coil while it is passing the gap between adjacent pole tips. It has been found that there will be inherent sparking due to self-induction, if the length of the armature core is more than 18 inches when the current exceeds 100 amperes. The length of the armature should also be such

as to make it possible to use either rectangular or square field cores. The advantage of round cores lies in the minimum amount of copper required to produce an ampere-turn thereon. Thus, let it be assumed that each of the cores, *A-B-C*, Fig. 517, has a cross-section of 5 square inches. To produce one ampere-turn on the core *A* will take say 10 inches of wire. The same ampere-turn may require but 8 inches of wire on the core *B*, while the core *C* would need but 6 inches. Now an ampere-turn is equally effective regardless of the length of the copper required to produce it, therefore it will take less copper to produce a given flux density with *C* than *B*, and less with *B* than with *A*. This follows from the general rule that "of all shaped figures enclosing equal areas, the circle has the minimum perimeter." From the standpoint of economy in field copper then, field cores should always be round. If round cores are employed, the pole face should preferably be square.

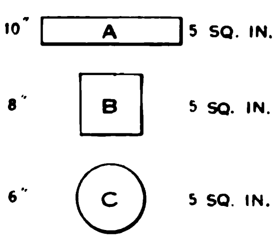


Fig. 517.

If the pole face is square, its length parallel to the armature core should equal the polar span around the armature circumference. The length of the armature is therefore related to the armature diameter and the number of poles. If the two dimensions of the polar face are equal, then the armature length should be:

$$L = \frac{\% D \pi}{p}.$$

L = armature length in inches.
$\%$ = percentage of armature circumference embraced by pole pieces.
D = armature diameter.
π = constant.
p = number of poles in field.

This equation gives the value of the armature length as that of one polar span, which is correct.

There is a great difference between machines with **solid poles** and those with **laminated poles.** With **solid poles it is necessary** that the **air gap be long** and the **slot width narrow to prevent pole face eddy currents.** Thus if the **slots are broad** and the

air gap short, the flux will bunch in front of the teeth and as the armature turns, the flux density will vary across the pole face as shown in Fig. 518. If, on the other hand, the **air gap is long** and the **slots comparatively narrow,** the flux will spread out on its way to the pole faces and occupy the entire face of the pole uniformly, as in Fig. 519. The rotation of the armature will now cause little variation in density on the pole face and there will be no eddy currents induced. If the slots are partially closed so as to narrow the gap at the armature's circumference, the air gap length may be shortened without producing eddy currents. With laminated poles it is possible to use **both short air gaps and wide open slots** at the same time. The laminating of the pole insures the breaking up of the eddy currents on the pole faces,

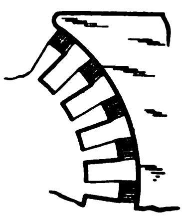


Fig. 518.

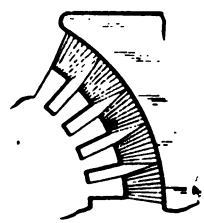


Fig. 519.

and the shortening of the air gap improves the efficiency. While the initial cost is greater than with solid poles, the efficiency in operation warrants it. The laminated pole usually has an air gap which is longer at the pole tips than at the pole center. This permits the gradual introduction of the teeth into the region of the field flux and makes a quieter running machine. In the absence of laminated poles it is customary to "nose off" the pole tip so that the teeth enter the field flux region gradually. In small machines the laminations are sometimes "skewed" so that they make the slot take a spiral direction along the armature length. Both of these methods accomplish the same result, that of making the machine operate more quietly.

Wide slots reduce inductance and have a tendency to improve commutation but with the wider slot, a larger number of coils must be placed in each slot. All of these coils cannot be commutated at once, and they all pass through the same polar region at the same instant. Therefore they must be commutated successively. The armature therefore turns a considerable angle

during the commutation of all the coils in one slot. It is not possible to set the brushes so that commutation of a large number of coils can be effected successfully. Thus with four coils in a slot it sometimes happens that every fourth segment will burn and blacken and the commutator wear unevenly. This difficulty restricts the permissible number of coils in a slot.

The flux density in the air gap should be as high as practical for this also is one of the factors of output. The density is limited by the magnetic saturation of the teeth and the relation which exists between the slot width and the tooth width. To have the flux density high, the percentage of armature circumference which is occupied by the slots must be relatively small, as shown in Fig. 515. The result will be to make the ampere-conductors per inch of circumference small. As this also is a factor of the output the watts produced will therefore be decreased. If, on the other hand, the percentage of armature circumference occupied by the slots is large, as in Fig. 516, the teeth will become very thin and the flux they will carry will be reduced. The flux density in the air gap must then necessarily be reduced also and again the output is decreased. Between these extremes a good medium is 40,000 to 60,000 lines of force. It may be as low as 25,000 in fan motors and as high as 75,000 in very large machines with laminated poles.

The ampere-conductors per inch of armature circumference is limited by the available space in the slots. It has been found that the armature I^2R losses may be objectionably large unless an allowance of from 500 to 600 circular mils per ampere is made for the current therein. While it is possible to keep the temperature down, by forced draft and good ventilation, the efficiency will usually be low if the circular mils per ampere is less. Fan motors may operate successfully with as low as 300 circular mils per ampere. Very large machines may require from 800 to 1,000 circular mils per ampere.

As a definite number of circular mils per ampere is required, it is obvious that the greater the number of ampere-conductors per inch of circumference, the greater the space that will be necessitated in the slots, but the slots cannot be made indefinitely deep. Now the deeper the slot, the greater the inductance and the greater the difficulty in radiating the heat. Moreover, the tooth tapers to a narrow root, thereby choking the flux. With

armatures of small diameter, comparatively shallow slots are required and therefore fewer ampere-conductors per inch of circumference are possible. Large machines permit the use of deeper slots and correspondingly more ampere-conductors per inch of circumference. The usual value for this quantity varies from 300 to 800. Fan motors may employ as low as 100.

The speed of commutating machines varies widely, depending upon whether they are direct connected to reciprocating engines, belt driven, or operated by steam turbines. A peripheral velocity of 4,000 to 6,000 feet per minute is not unusual. The speed in r.p.m. is based upon an estimated circumferential velocity and will be expressed by the equation

$$S = \frac{v \times 12}{\pi \times d}.$$

Where:

S = speed in revolutions per minute.
π = 3.1416.
d = diameter of armature in inches.
12 = constant to change feet to inches.
v = peripheral speed in feet per minute.

It is more difficult to wind machines for high voltages than for low, because high voltage windings require more space in the slot on account of the added insulation. Hence if values have been assigned in the fundamental equation for a given output in watts, the frame structure should first be designed to carry the highest voltage winding for which the machine is to be built and then no difficulty will be experienced in adapting the same structure to lower voltages.

SECTION XIII CHAPTERS I AND II

DESIGN OF DIRECT-CURRENT MACHINES

FUNDAMENTAL PRINCIPLES

1. Explain what is meant by flux capacity and current capacity in a generator. How are they related to each other and to the capacity of the machine?

2. How does the diameter of an armature affect the flux capacity? How does the length of an armature affect the flux capacity?

3. How does the diameter of an armature affect the ampere-conductor capacity? How does the length of an armature affect the ampere-conductor capacity?

4. What are the relative advantages and disadvantages of laminating field poles?

5. Should field magnet cores be round, square or rectangular? Give reasons in full.

6. What advantages, if any, come from "nosing off" the shoes of field magnet poles?

7. What advantages, if any, come from making the air gap length greater at the pole tip than at the pole center in a field magnet structure?

8. What governs the length of an armature? What limits the maximum length?

9. What is a suitable flux density in the air gap in various size machines?

10. What is a fair allowance for the ampere-conductors per inch of armature circumference? What governs this allowance?

11. At what speed may generators be driven?

ALTERNATING CURRENTS

PRINCIPLES OF ALTERNATING CURRENTS

With the exception of acyclic generators, as has been previously stated, all dynamo electric machines inherently generate alternating voltages and produce in their windings alternating currents. If then, a conductor on an armature sweeps across a pole face, a wave of voltage is induced which will urge a current in a given direction. As this conductor moves across the face of the succeeding pole having opposite polarity, a corresponding wave is developed in the opposite direction. Thus, voltage and current alternate as the conductor passes each succeeding pole.

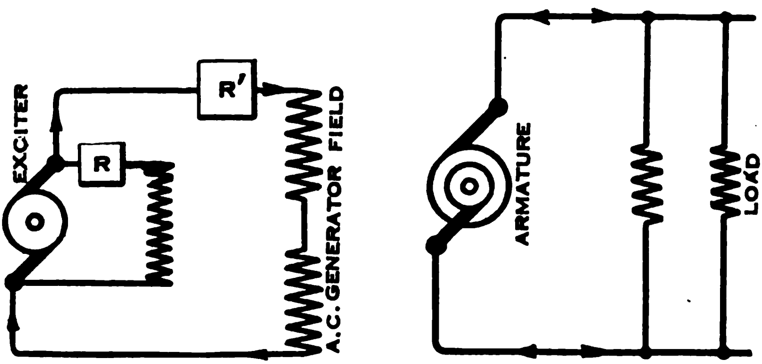


FIG. 520.—Alternating current generator with its field separately excited from direct current exciter.

As pointed out, this current is rectified through a commutator for purposes requiring a continuous current, as in charging of storage batteries and the operation of D. C. motors. For many other classes of work, alternating current is preferred. An alternating current is one which periodically reverses its flow. No commutator will be required in such a machine but the moving armature conductors may be permanently connected with the external circuit through sliding connections, and the current will reverse in the same manner in the external circuit as it did within the machine.

Alternating current is not suitable for field magnetizing purposes, hence alternators are provided with exciters as shown in Fig. 520. This is usually a small direct-current generator

with a capacity of from 5 to 10% of the capacity of the alternator which it excites. It may be driven by a separate source of power such as an electric motor, steam engine or turbine, or it may be direct connected to the shaft of the alternator or built within the same frame structure. It is, however, an independent machine. Exciters are usually from 110 to 250 volt generators. The larger alternators employ the higher voltage exciters. The current from the exciter is led through a field rheostat R' to the field windings of the alternator. Alternators are usually constant potential machines for they are driven at a constant speed and have a fixed field strength. Their voltages are held very close to the desired value by means of special regulators. The usual voltages for which alternators are constructed are 2,200, 6,600 and 11,000. Higher voltages for transmission of power purposes are available, these being obtained by means of transformers.

The manner in which the alternating e.m.f. is produced must be carefully considered. In Fig. 521, the conductor A is supposed to be rotating in a simple bipolar magnetic field, in the direction indicated by the arrow. As it moves into the positions B-C-D-E, it cuts the lines of force of the field at an increasing rate. The instantaneous value of the voltage generated by a coil in any particular position is proportional to the rate of change of the flux within the embrace of the coil. This in turn is **proportional to the sine of the angle** which the conductor makes at that particular moment with the starting point. The area of flux within the embrace of a coil consisting of conductors, A-K, is proportional to the cosine of the angle which these conductors make with the starting point. When the conductor reaches the position B, the voltage is measured by the line B-F, which represents the sine of the angle of 22½ degrees. When the conductor reaches the point C, the instantaneous voltage is measured by the line C-G. When it reaches D, D-H measures the voltage and at E the voltage is measured by E-O. The way in which the voltage varies may be graphically represented by a curve constructed with rectangular coordinates. Thus, lay off a line A-A'-A'', equal to 360 degrees and corresponding to the circumference of the circle through which the conductor moves. At the point F (22½ degrees from A) erect an ordinate B-F, proportional to the sine of the angle which the conductor

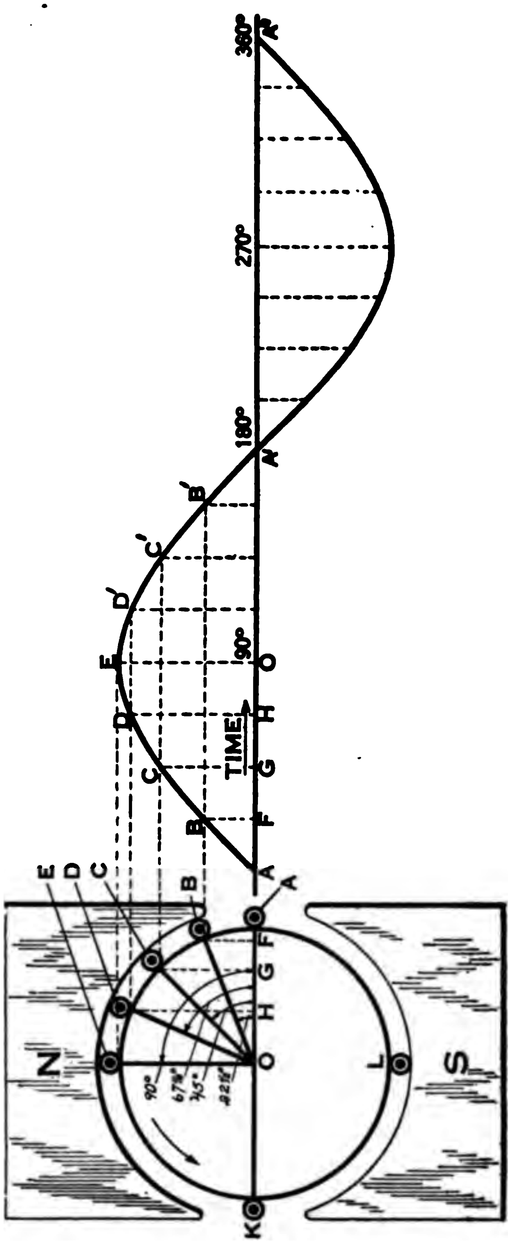


FIG. 521.—Sine wave of e.m.f. produced by one revolution of conductor on armature in a bipolar field.

B makes with the starting point *A* at that instant. At the point *G* (45 degrees from *A*) erect an ordinate *C-G*, which is proportional to the sine of the angle of 45 degrees, which the conductor *C* makes at this instant with the starting point. At the point *H* (67½ degrees from *A*) erect the ordinate *D-H*, corresponding to the voltage generated at *D*, and likewise at the point *O*, erect the ordinate *E-O*, corresponding to the voltage generated at *E*. Now connect the tops of these ordinates by a line and the curve *A-B-C-D-E* will be obtained. This shows how the voltage will vary while the conductor *A* moves through a quarter of a revolution. The voltage will fall in a corresponding manner while it moves from *E* to *K* and this is shown by the descending curve *E-D'-C'-B'-A'*. As the conductor moves from *K* to *A* it will pass backward across the field and the variation of voltage will be represented by a curve in the reverse direction from *A'* to *A''*. In a simple circuit the current would rise and fall in a similar manner so that this curve would show either the variation of voltage or the variation of current produced thereby. It is called a "sine" curve because the variation of the voltage in a uniform field follows the sine law. Such a curve is not peculiar to alternating currents and voltages. It is characteristic of any periodical movement. The pendulum of a clock oscillating to and fro could be made to trace a similar curve upon a paper drawn underneath a pencil projected therefrom, the motion of the paper being at right angles to the motion of the pendulum.

The question will naturally arise: What voltage will be indicated by a voltmeter connected in such a circuit? Obviously the needle would not indicate the maximum value of the wave because this value is maintained only momentarily. Neither would it indicate zero for the inertia of the needle would not not allow it to sink to zero value. It would naturally be expected that a voltmeter would indicate the average height of the wave. This would be obtained by adding together the values of all the several sines of the various angles and dividing by the number of separate sines so combined. This average of all the sines is 0.636 of the maximum. Thus, if the **maximum** height of the voltage wave in an alternator were 1,000 volts, as in Fig. 522, the **average** voltage would be 636. The instrument does not show this value, however. The actual voltage

is determined in a rather peculiar way. An alternating current and a direct current are considered of equal value provided they produce the same heating effect. The heating effect is proportional to the square of the current. Now it has been found that the heating effect in a circuit carrying an alternating current of sine wave formation and having a maximum value of 1,000 amperes is the same as the heating effect of a continuous current of 707 amperes. An ammeter in an alternating circuit would indicate 707 amperes if the maximum height of the current wave were 1,000 amperes and this indication would correspond to a direct-current ammeter showing 707 amperes, for the two currents would produce the same amount of heat. To arrive

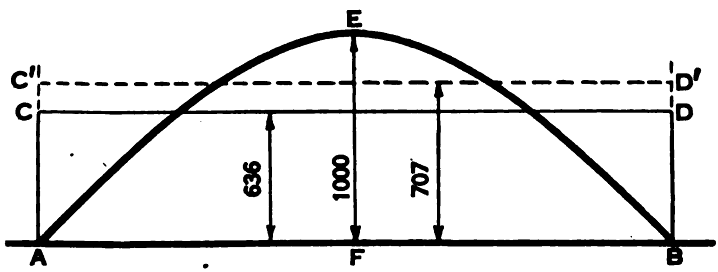


FIG. 522.—*A–C* = average e.m.f.
A–C' = virtual e.m.f.
F–E = maximum e.m.f.

at this value it is necessary to square each of the separate instantaneous values of the current corresponding to the sines of the various angles. These squares are then added and the sum divided by the number of separate values taken. From this sum the square root is extracted. The result is 0.707 of the maximum value of the current or voltage. This is called the "square-root-of-mean-square" or *r.m.s.* value. That is, the voltmeter or ammeter will indicate the **square root of the average of the squares** of all the separate instantaneous values of the voltage or current while the conductor is passing from *A* to *E*.

This may be viewed in another way. When the conductor is passing the point *C*, Fig. 521, it makes an angle of 45 degrees with the starting point *A*. Now the sine of 45 degrees is 0.707 and this is the value which the ammeter or voltmeter will show. That is to say, instead of the instrument indicating the average of the sines of all the separate angles it indicates the **sine of the average angle.**

If a transmission line operates at 100,000 volts as registered on the voltmeter, it must be borne in mind that twice in each cycle the voltage rises to 141,000 volts, although the voltmeter shows only 100,000 volts, for it indicates the **virtual** and not the maximum voltage. Nevertheless, the insulation is subjected to a potential strain corresponding to the maximum height of the e.m.f. wave. This necessitates that the winding of all alternators, transformers, and the construction of the insulators for the line itself, shall all be designed to withstand 41% greater voltage than that indicated by the voltmeter.

If an ammeter indicates 100 amperes in an alternating system, twice in each cycle the current rises to a maximum of 141 amperes. In this case it is not necessary to provide additional copper to take care of the additional heating due to the maximum height of the current wave, because the diminished heating when the current is varying from zero to 100 amperes exactly offsets the additional heating when the current is varying from 100 to 141 amperes, so that the total heat generated in the copper is as though a continuous current of 100 amperes flowed therein.

When a conductor starts at the point A, Fig. 521, moves to E, and then to K, the voltage and current start at zero, rise to a maximum value and sink to zero again. The wave of voltage or current thereby produced is termed an **alternation.**

When the conductor continues to the point L and then to A, the voltage and current complete another alternation in the reverse direction. These two successive alternations constitute a **cycle.** A cycle is completed by the voltage and current in a conductor during one revolution in a bipolar field, or when the conductor passes through 360 electrical degrees in a multipolar field. The symbol $\backsim$ is used for the cycle.

The **period** of an alternator is the time required for the execution of a cycle. The period of most alternators is either $\frac{1}{25}$ or $\frac{1}{60}$ of a second.

The **frequency** of an alternator is expressed in cycles per second or alternations per minute. The common frequencies of most alternators are 60 cycles per second or 7,200 alternations per minute and 25 cycles per second or 3,000 alternations per minute.

Two car wheels on the same axle of a street car revolve in **synchronism.** That is, they complete the same number of rev-

olutions per minute. On a curve one of the wheels must slip to accommodate itself to the different radii of the two rails, for the two wheels must revolve precisely alike. The two wheels on an automobile do not revolve synchronously. The differential permits them to run at different speeds on a curve and thus avoids the necessity of one slipping. Two alternating-current machines are said to revolve synchronously if a certain conductor on each machine passes the center of a north pole at the same time in both machines, the center of a south pole at the same time and so on continuously. This would be effected if the two armatures were rigidly connected like the two wheels on a car axle. If one of these conductors was displaced with respect to the other through an angle of 90 degrees the shafts might still be rigidly coupled so that the two machines would rotate synchronously and yet there would be a displacement of 90 degrees between the two conductors.

The **phase** or **phase-angle** of a conductor is the angle which it makes with the starting point. Thus, in Fig. 521, the conductor E makes a phase-angle of 90 degrees with the conductor A, or the relative positions of the two conductors may be described by stating that the conductor A is 90 degrees in phase behind the conductor E.

SECTION XIV CHAPTER I

ALTERNATING CURRENTS

PRINCIPLES OF ALTERNATING CURRENTS

1. What is the nature of the e.m.f. wave produced by an ordinary alternator? Explain how a sine wave is constructed.

2. In an alternator, distinguish between the maximum e.m.f., the virtual e.m.f. and the average e.m.f. What e.m.f. is registered on the voltmeter?

3. In an alternator circuit an ammeter reads 1,414 amperes. What is the average, virtual and maximum current?

4. An alternating current voltmeter registers 2,200 volts. What is the average, virtual and maximum e.m.f.?

5. Define "alternator"; "cycle"; "period"; "frequency."

6. Define "phase" and "synchronism." Give an illustration involving both terms.

SECTION XIV CHAPTER II

ALTERNATING CURRENTS

INDUCTANCE AND REACTANCE

Inductance is an inherent property of a coiled resistance by virtue of which it opposes any change of current in the circuit. Three things should be emphasized in analyzing this definition:

First: It is an **inherent** property, that is, it is peculiar to a coil. A straight wire 100 feet long possesses practically no inductance, but if that wire is wound into a coil this property is immediately developed.

Second: It is a **kind** of **resistance** for it offers an opposition to the current.

Third: It does not oppose the flow of a **continuous** current of fixed value but it opposes any **change** in the value of the current.

The inductance of a coil is greater when the coil has 50 convolutions than when it has 10. It is greater with a coil of large diameter than with one of small diameter. It is greater when the coil has an iron core than when it has an air core. Thus, increasing the number of convolutions in the coil, the diameter of the coil or the permeability of the core all tend to increase the inductance thereof, but the coil possesses this property of inductance **before** any current is introduced into it. The unit of inductance is the **henry.** Its symbol is L. A coil possesses an inductance of one henry when a current varying at the rate of one ampere per second causes the induction therein of one volt.

Reactance is the direct result of inductance without which it cannot exist. If an attempt is made to force a current through a coil possessing inductance, reactance is immediately encountered. The amount of reactance encountered depends upon two things:

First: The inductance of the coil, in henries, L.

Second: The frequency in cycles per second at which the current alternates. It will be observed that the reactance is dependent upon the **rate of change** of the current. Reactance like resistance is expressed in ohms. The product of the inductance, L, the frequency, n, and a constant is equal to the reactance

in ohms. Reactance ohms are equivalent to resistance ohms in their effect of limiting the current. The symbol for the magnetic reactance in ohms is X.

When an alternating e.m.f. is impressed upon a circuit the current which flows is not equivalent to the electro-motive-force divided by the resistance of that circuit alone, as in direct-current circuits, but the current is equal to the electro-motive-force divided by the joint effect of the resistance ohms and the magnetic reactance ohms. This combined effect is called **impedance.** The symbol is Z. Thus, while in a direct current circuit, $I = \frac{E}{R}$, in an alternating circuit, $I = \frac{E}{Z}$.

The current produced in an alternating current circuit by a sine wave of e.m.f. will have the same general form as the voltage wave. If a circuit having a resistance of one ohm is con-

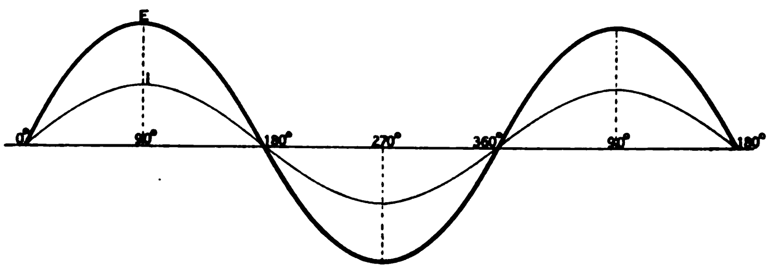


FIG. 523.—Sine wave of e.m.f. and current wave appertaining thereto.

nected to an alternator delivering 100 volts, then 100 amperes will flow. This current would start with zero e.m.f., rise to a positive maximum when the voltage was maximum, fall to zero with the voltage, reverse to a negative maximum, and again sink to zero with the voltage, as in Fig. 521. The curve in Fig. 521 will thus represent either the voltage generated or the current produced thereby in a circuit where resistance only is present. If the resistance of the circuit were 2 ohms, then a current of only 50 amperes would be produced, but the current and voltage would still start at the same time, reach their maximum and zero values at the same time as in Fig. 523.

The starting and stopping of the current which is continuously taking place in A. C. circuits produce great changes in the electro-magnetic stresses about the conductors and these changes in turn produce very important reactions. They give the

alternating current its most valuable properties but also bring about many curious complications. Consider an alternator, Fig. 524, connected to a circuit including a coiled resistance, *B-C-D-E*. Assuming an alternating e.m.f. to be impressed upon this circuit, the resulting current begins to rise simultaneously in the conductors *B-C-D-E*. This current produces loops of magnetic force which expand from each convolution of the coil and cut across all of the other convolutions. This induces an e.m.f. which in accordance with Lenz's Law is opposed to the **rising** current. When the current finally reaches its maximum value the magnetic flux within the coil is for a moment stationary. At this moment the induced e.m.f. ceases.

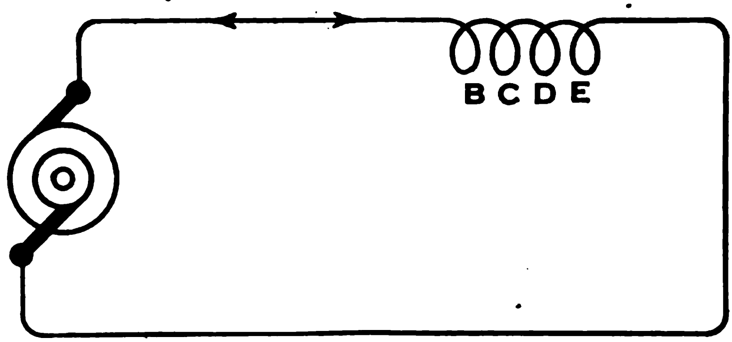


FIG. 524.—Alternator supplying inductive circuit.

When the current commences to fall, the loops of magnetic force collapse upon the conductors and generate an e.m.f. which is likewise opposed to the **fall** of the current.

The impressed e.m.f. is thus opposed in all of its **changes** by the inductive e.m.f. generated in the coil. Thus the impressed e.m.f. has to overcome not only the ohmic resistance of the coil but an opposing electro-motive-force generated therein. Therefore since a part of the impressed e.m.f. is consumed in overcoming the inductive e.m.f., only the remainder is effective in forcing the current through the ohmic resistance of the circuit. Ohm's Law therefore, cannot apply to an inductive circuit in which an alternating current flows except by considering the effective e.m.f. The relation between the impressed e.m.f. and the current, then, is not $I = \frac{E}{R}$, but $I = \frac{E}{R}$ **less a certain quantity**, depending upon the amount of inductive e.m.f. encountered.

The conditions are similar to those found in a direct current motor, where the impressed e.m.f. causes the armature to revolve and thereby generate a counter e.m.f., which opposes the impressed. The net difference between the counter and the impressed is the effective e.m.f. This is the voltage that actually overcomes the resistance of the circuit. In the case of the motor the conductors move while the flux is stationary. In the case of the coil in Fig. 524, the flux moves while the coil is stationary. Now this inductive e.m.f. follows the same form of the sine wave as that generated in the alte nator and pictured in Fig. 521, for the conductor in moving through the field generated a sine wave of voltage and current. When this sine wave of current is introduced into the coil *B-C-D-E* in Fig. 524, there will result a sine wave of flux. The variation of this sine wave of flux therefore generates a sine wave of inductive e.m.f. This assumes that the coil has an air core.

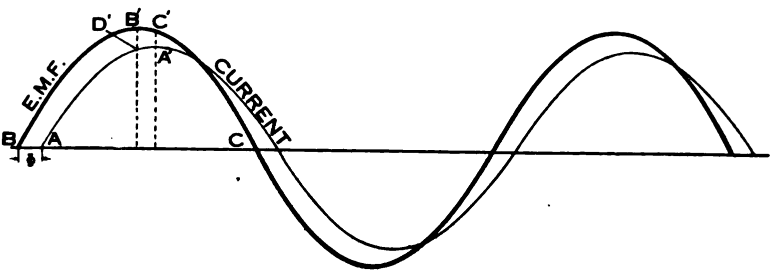


FIG. 525.—Illustrating current wave damped in amount and displaced in phase from e.m.f. wave due to inductance in circuit.

The result of inductance in alternating circuits is two-fold:

First: The current is less than the impressed e.m.f. would indicate, for the opposition is equivalent to an actual reduction of the impressed e.m.f.

Second: This current reaches its maximum later than the impressed e.m.f., for the current actually depends upon the effective e.m.f. and for each particular value of the effective e.m.f. the impressed e.m.f. must have had time to rise high enough to overcome the corresponding value of the inductive e.m.f. The current is thus damped in amount and caused to lag in phase as shown in Fig. 525. The distance *A-B* represents the angle by which the current lags behind the e.m.f. That is, the current reaches its maximum *A'* later than the voltage,

which reaches its maximum at B'. Likewise the current at D' is less than its maximum while the voltage is a maximum at B'. This angle between the current and the e.m.f. is called the **angle of lag.** It is represented by the Greek letter Φ. It varies with the inductance of the alternating circuit.

As has already been pointed out, the inductive e.m.f. is due to the magnetic changes produced by the variation of the current. As in the alternator the actual e.m.f. is proportional to the rate of change in magnetic stress, so in the coil the e.m.f. is proportional to the rate of cutting magnetic lines and this in turn is proportional to the rate of change of current. The

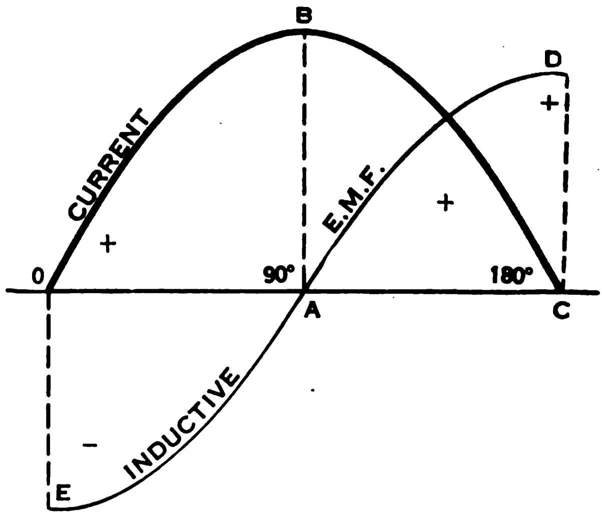


FIG. 526. -Inductive e.m.f. lagging 90° behind current.

inductive e.m.f. at any instant is then proportional to the rate of change of the current. The rotation of the conductor through the field in Fig. 521 resulted in the generation of a sine wave of e.m.f. This e.m.f. impressed upon the coil in Fig. 524 brings about a sine wave of current. This current as it rises and falls produces a sine wave of flux. This sine wave of flux alternating about the convolutions of the coil generates in the coil a sine wave of voltage. Thus the inductive e.m.f. in the coil *B-C-D-E* is the replica of the generated e.m.f. in the alternator.

The phase relation between this inductive e.m.f. and the current whose variations induce it will now be considered. In

Fig. 521 the current varies most slowly when it has its maximum value at E. The flux due to this current in the coil in Fig. 524 is therefore stationary at this instant and the voltage induced will be zero. This fixes the point of zero induced e.m.f. at A in Fig. 526, when the current has its maximum value at B. In Fig. 521 the current is varying most rapidly when it has its zero value at A'. The flux due to this current in the coil in Fig. 524 will then be varying most rapidly and the induced e.m.f. will therefore be a maximum. This fixes the maximum value of the induced e.m.f. in Fig. 526 at the time of zero current. The inductive e.m.f. is therefore displaced in phase 90 degrees from the current, for the inductive e.m.f. is zero at A and the current has zero value at O and these two points are 90 degrees apart in phase. It must now be decided whether the inductive e.m.f. is 90 degrees ahead or 90 degrees behind the current. This may be determined as follows: While the current in the coil is rising in a positive direction from O to B, the induced e.m.f., according to Lenz's Law, must be in the direction opposed thereto, or in the negative direction. Hence it is represented by the curve E-A. When, however, the current passes its crest at B and commences to fall in a positive direction, from B to C, the induced e.m.f. reverses, that is, in a positive direction from A to D, thereby tending to sustain the current, for the induced e.m.f. is not opposed to the **current** but to the **changes** in the current. If the current is trying to fall, the induced e.m.f., rising, opposes its fall. These facts establish the inductive e.m.f. at its maximum value in a positive direction at D, while the maximum value of the current is in the same direction at B. Now, as time progresses from O to C, the inductive e.m.f. lags 90 degrees in time phase behind the current. That is, it reaches the point D, 90 degrees later in the cycle than the current reaches its maximum, B.

In an inductive circuit there are three e.m.fs. to be considered:

First: The **impressed** e.m.f. acting upon the circuit.

Second: The **inductive** e.m.f. opposing the impressed.

Third: The **effective** e.m.f. which is the resultant of the interaction of the impressed and the inductive.

These three e.m.fs. may be plotted in curves showing the relation which they bear to each other as in Fig. 527. Here is shown the curve of the impressed e.m.f. with the effective e.m.f.

lagging behind it, through the angle Φ. The effective e.m.f. is responsible for the current and is always in phase with it. Then comes the inductive e.m.f. lagging 90 degrees behind the effective e.m.f. and the current.

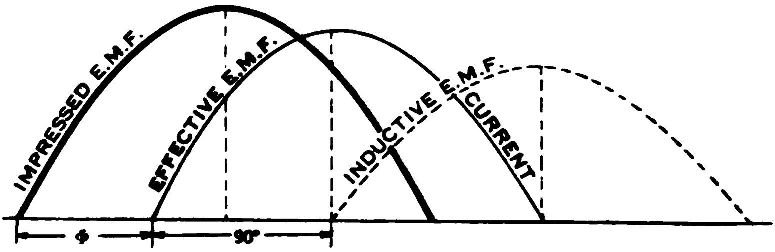


FIG. 527.—Relative phase relations of impressed e.m.f., effective e.m.f., and inductive e.m.f.

Now as the effective e.m.f. is the resultant of the interaction of the impressed e.m.f. and the inductive, and it is definitely known that the effective and the inductive are 90 degrees apart in phase as previously pointed out, the exact relation between the three forces can be very readily shown.

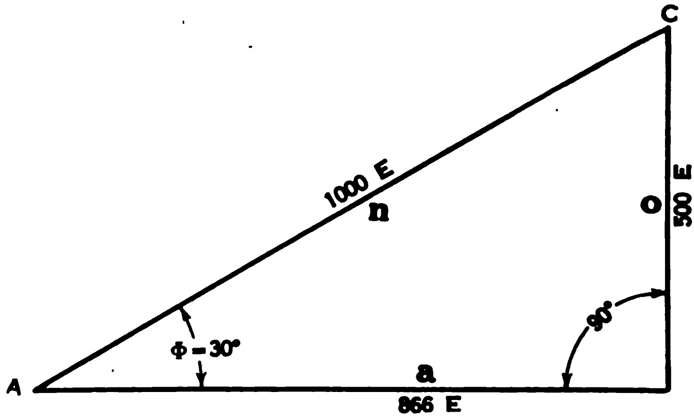


FIG. 528.

Electro-motive-forces acting at definitely known angles to each other may be represented by lines whose length and direction represent the magnitude and direction of the corresponding electro-motive-forces. Thus, in Fig. 528, let *A-B* represent the effective e.m.f. and *B-C* the inductive e.m.f. displaced in phase 90 degrees therefrom. *A-C* will represent the impressed

e.m.f. which is resolved in the diagram into the two components A-B and B-C. From trigonometry the following expressions are obtained:

$$\frac{AB}{AC} = \cos \Phi. \quad \text{Therefore } AB = AC \times \cos \Phi.$$

$$\frac{BC}{AC} = \sin \Phi. \quad \text{Therefore } BC = AC \times \sin \Phi.$$

Suppose that the alternator in Fig. 524 impresses 1,000 volts upon the circuit and, due to the inductance encountered in this circuit, the current lags 30 degrees behind the impressed e.m.f. This angle can be readily ascertained by means of suitable instruments as will be explained later. From a table of natural sines, the sine of 30 degrees is found to be 0.5 and the cosine of

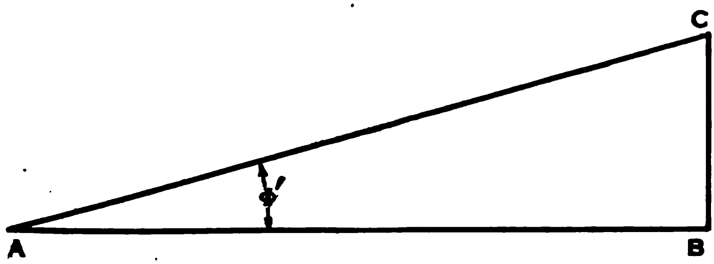


FIG. 529.

30 degrees, 0.866. Applying the formulas given, the inductive e.m.f., B-C, is equal to the impressed e.m.f., A-C, multiplied by the sine of 30 degrees. Thus, $1{,}000 \times 0.5 = 500$ volts. The effective e.m.f., A-B, is equal to the impressed e.m.f., A-C, multiplied by the cosine of 30 degrees, thus: $1{,}000 \times 0.866 = 866$ volts. Knowing any two of the four quantities given, the other two may readily be determined. The effective e.m.f. in a circuit then is ascertained by multiplying the impressed e.m.f. by the cosine of the angle of lag. Should the inductance in the circuit be reduced, as for example by reducing the number of convolutions in the coil shown in Fig. 524, the inductive e.m.f. would drop from the value shown in Fig. 528 to the value shown in Fig. 529. This causes the angle of lag to drop from Φ to Φ'. As the angle grows less and less the impressed e.m.f. necessary to produce a given current also decreases and when Φ finally becomes zero, A-C = A-B, which means that the

impressed e.m.f. is simply that needed to overcome the ohmic resistance of the circuit. For a given current, *A-B* is directly proportional to the **resistance** of a circuit and *B-C* is directly proportional to the **reactance** of the circuit.

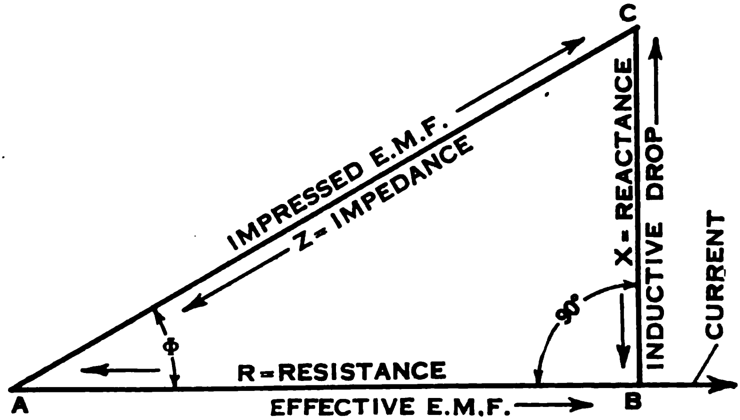


FIG. 530.—Phase relation between the various e.m.fs. in an inductive circuit and the forces which they overcome.

Fig. 530 shows the opposing forces which the various electromotive-forces are employed to overcome in an inductive circuit. Thus the impressed e.m.f. *A-C*, acting upon the circuit,

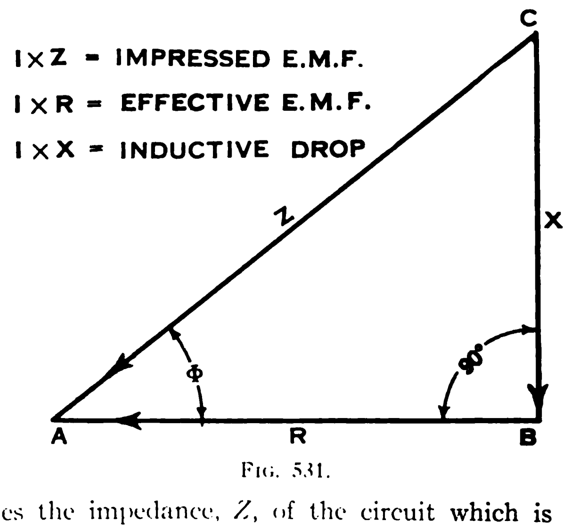


FIG. 531.

overcomes the impedance, *Z*, of the circuit which is in direct opposition thereto. This impressed e.m.f. is split up into two components, one of which, *A-B* (the effective component), over-

comes the resistance of the circuit, the other, B-C (the inductive component), overcomes the reactance of the circuit. The current, I, is in the same direction A-B as the effective e.m.f., for the effective e.m.f. is responsible for the current and is always in phase with it. These related forces may now be separated into two triangles, one the impedance triangle, Fig. 531, and the other the e.m.f. triangle, Fig. 532. The angle of lag, Φ, is the same in both cases. The connecting factor between these two triangles is the current.

As the relation between the resistance of the circuit, R, and

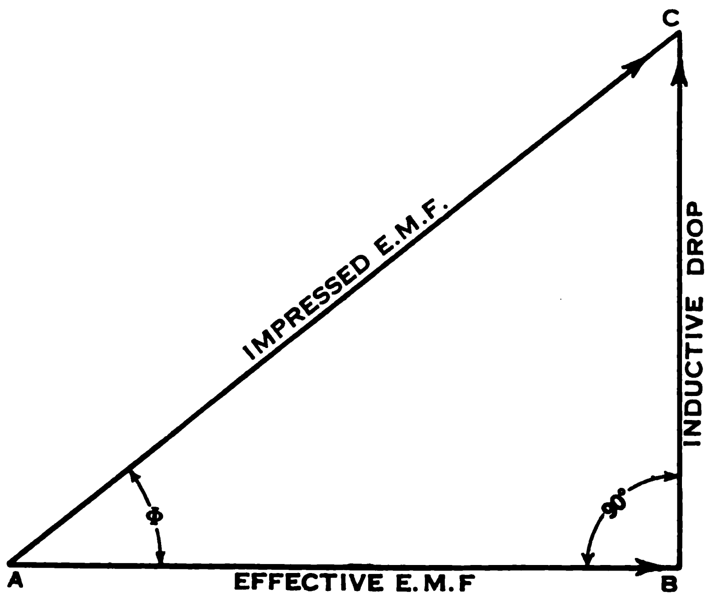


FIG. 532.

the reactance of the circuit, X, is always 90 degrees, it is evident that the impedance of the circuit Z is, $Z = \sqrt{R^2 + X^2}$. If X becomes zero, Φ becomes zero and $Z = R$; that is, the impedance is simply the resistance of the circuit. Ohm's law for an alternating-current circuit containing only resistance is then:

$$I = \frac{E}{R}.$$

But if the circuit is inductive it will be:

$$I = \frac{E}{Z}$$

and as Z is composed of both resistance and reactance, with the fixed phase relation previously shown, the current in such a circuit becomes

$$I = \frac{E}{Z} = \frac{E}{\sqrt{R^2 + X^2}}.$$

In a circuit of given inductance, increasing the resistance diminishes the angle of lag but it also diminishes the current for a given value of E. Thus, if A-B, Fig. 533, represents the resistance of a circuit, and B-C, the reactance, then the current that would be produced with a given voltage would be limited by the impedance, A-C. But if the resistance in this circuit were increased to A-B, Fig. 534, while the reactance, B-C, was maintained the same, the angle of lag, Φ, would be reduced to Φ' while the impedance, A-C, would be increased. Obviously, for the same impressed voltage, the current would be reduced.

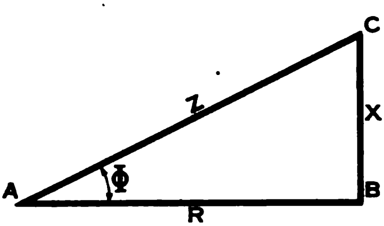


FIG. 533.

No energy is expended in forcing the current through the reactance as the inductive voltage simply represents a value which is geometrically deducted from the impressed voltage.

For a given value of impressed e.m.f., any change in the circuit which involves an actual increase in the energy expended in that circuit must result in a diminished angle of lag.

The fact that no energy is involved in the production of the inductive e.m.f. may be proved in the following way: The factors of power are current and voltage and there can be no real energy when the product of these two factors is zero. In Fig. 526 during an alternation of current it will be observed that the inductive e.m.f. is equally above and below the line. The average value of the inductive e.m.f. throughout the alternation of the current is therefore zero. The product of the current and zero e.m.f. will therefore be zero power as far as the interaction of the current and inductive e.m.f. are concerned. Between O and B the current is rising in a positive direction. During this time the inductive e.m.f. is in a negative direction, from E to A, and is opposing the current's rise, while between B and C the current is falling in a positive direction and the inductive e.m.f.

is rising from A to D in the same direction; that is, it is opposing the current's **fall.** Thus, during the first quarter of the cycle, the inductive e.m.f. opposes the current's rise and during the second quarter of the cycle the inductive e.m.f. assists in maintaining the current. The average effect of the inductive e.m.f. is therefore to neither aid nor oppose the current, but is zero.

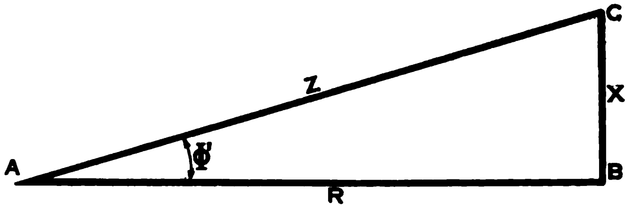


FIG. 534.

Therefore, when the question of work done in an alternating circuit is considered, the inductive e.m.f. does not enter into the calculation. Furthermore, the effective e.m.f. only differs from the impressed e.m.f. by the inductive e.m.f., the energy value of which is zero. The true power in a circuit must then be measured by the effective e.m.f. and the current which is in phase with it, but as has already been pointed out, the effective e.m.f. is equal to the impressed e.m.f. multiplied by the cosine Φ. Multiplying both sides of this equation by I to reduce to energy gives

$$I \times \text{Impressed e.m.f.} \times \cos \Phi = I \times \text{Effective e.m.f.}$$

That is, the energy in an alternating circuit is not simply the product of the current and the impressed e.m.f. but is equal to the product multiplied by the cosine of the angle of lag existing between the current and the impressed e.m.f. The product of the line current and the impressed e.m.f. is called the **apparent energy** in the circuit. The product of the line current and effective e.m.f. is the **real energy.** The apparent energy is the product of the readings of the voltmeter and ammeter. The **true energy** is obtained from a **wattmeter** reading. Transposing the above formula will give:

$$\frac{\text{Watts}}{\text{Volt-amperes}} = \frac{\text{Real energy}}{\text{Apparent energy}} = \cos \Phi.$$

This cosine of Φ is called the **power factor.** As above stated it is the ratio of the real energy to the apparent energy. It

expresses that percentage of the apparent energy which is real in an alternating circuit. Thus, in Fig. 535 an ammeter might show 10 amperes and a voltmeter 100 volts, while a wattmeter indicates 900 watts. The power factor in this case would be:

$$\frac{P}{EI} = \frac{900}{100 \times 10} = 0.90 \qquad 0.90 \times 100 = 90\%.$$

The reason that the wattmeter does not show the product of the voltmeter-ammeter readings may be seen from a consideration of Fig. 525. The ammeter shows the true current which reaches its maximum value at the point A'. The voltmeter shows the true voltage which reaches its maximum value at the point B'. Now these two factors of power reach their maximum values at different times because the current lags behind the voltage by the angle Φ. The wattmeter takes account of this difference due to the fact that the current and potential coils interact upon each other. Thus, when the e.m.f. in the potential coil has reached the point B', the current has only reached the point D'. A little later the current reaches its maximum at the point A' by which time the voltage will have fallen from its maximum to the point C'. Thus, the wattmeter

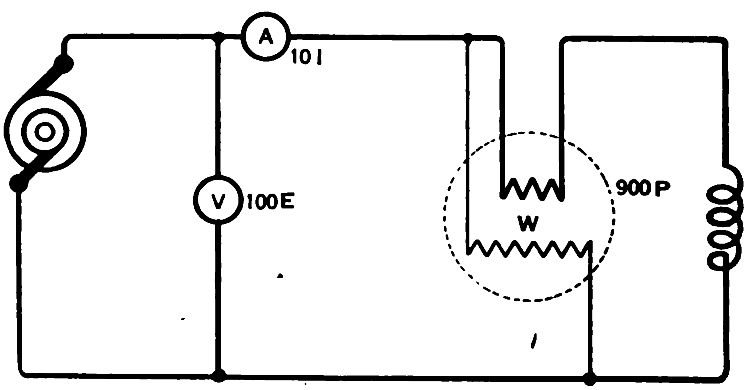


FIG. 535.—Relative indications of wattmeter, voltmeter and ammeter in inductive circuit.

indicates the true power at any instant and takes into account the phase angle between the current and the voltage, while the voltmeter knows nothing about what the ammeter is doing and the ammeter gives its indication without regard to the particular phase of the voltage.

The energy in an inductive circuit is therefore not directly proportional to the impressed voltage but to the effective voltage which is the geometrical difference between the impressed and the inductive drop encountered in the line. The voltage required to drive a given current through an inductive circuit will therefore depend upon the impedance of the circuit, or if the two circuits are supplied with a fixed e.m.f. it will require more current to represent a given amount of energy in the one possessing inductance than would be required in a non-inductive circuit. The practical result, then, of inductance in an alternating system is to increase the voltage which the generator must produce in order to deliver a given e.m.f. to the load and to likewise increase the current required to deliver a given amount of energy.

The alternator must thus be able to furnish a little extra voltage and both alternators and motors in the circuit must be able to stand a little extra current. In fact, both alternators and motors must have sufficient margin in capacity to take care of the matter of lagging current.

As an alternator may be called upon to carry a heavy inductive load where the current is greatly displaced from the e.m.f., the actual watts which the machine delivers may fall far below the product of its volts and amperes. A manufacturer will then not be able to rate his machines in kilowatts, because of the uncertainty of the power factor. The real basis for rating is the volts times the amperes. Alternators are therefore sometimes rated in **kilo-volt-ampere** (K.V.A.) capacity instead of **kilowatt** (K.W.) capacity. The true kilowatts obtained in any case is equal to the product of the kilo-volt-amperes, and the power factor. If the power factor is 100%, the kilowatts will equal the kilo-volt-amperes, but if the power factor is but 50%, then the true energy is only one-half of the kilo-volt-amperes which the machine is called upon to supply. Large A.C. generators are frequently rated in kilowatts at a definite power factor, usually 80%. This is because the limiting temperature of the field may be reached at this point. The field current required depends on the power factor as well as on the load and the kilo-volt-ampere rating may not express the limits of the machine.

At one time, because of the heavy inductive loads, some early

stations were receiving pay for not more than one-third of their kilowatt capacity. The efforts of designing and operating engineers is toward the improvement of the power factor in apparatus and upon the system as a whole in order that the kilo-volt-ampere capacity of a system may be more fully realized in kilowatts.

SECTION XIV CHAPTER II

ALTERNATING CURRENTS

INDUCTANCE AND REACTANCE

1. Explain the property of an electrical circuit known as "inductance." Give an illustration showing the effect of increasing the number of convolutions in a coil, or varying the material used for the core of a coil, upon the inductance of a circuit.

2. What is the effect of inductance in an alternating circuit upon the magnitude and phase relation of the current with regard to the impressed e.m.f.? Explain fully.

3. Define "magnetic reactance." Upon what does it depend?

4. Define "impedance." Explain what quantities constitute the impedance in an alternating circuit.

5. What is the angle between the current and the "inductive e.m.f." in an alternating circuit? Explain why this particular angle exists. Is it an angle of lag or an angle of lead? Explain fully why.

6. What three electro-motive-forces are found in an alternating current inductive circuit? What relation do they bear to each other?

7. In a certain alternating circuit, the current lags 30 degrees behind the impressed e.m.f. If the impressed e.m.f. is 2,200 volts, what is the value of the effective e.m.f. and the inductive e.m.f.? (The sine of 30 = 0.5 and the cosine = 0.866).

8. Distinguish between the inductance of a circuit, the reactance of a circuit, and the inductive e.m.f.

9. If the resistance of a circuit is 3 ohms and the magnetic reactance 4 ohms, what is the impedance?

10. What is the phase relation between the "inductive e.m.f." and the "inductive drop" in a circuit?

11. What is the phase relation between the effective e.m.f. and the current in a circuit?

12. What is the phase relation between the resistance and the effective e.m.f. in a circuit?

13. What is the phase relation between the reactance, the inductive e.m.f. and the inductive drop in a circuit?

14. What is the phase relation between the impedance and the impressed e.m.f. in a circuit?

15. An alternator possesses an armature inductance of 0.03 henry and a resistance of 4 ohms. It has 60 poles in its field and runs 120 r.p.m. What is its impedance?

16. Give the expression for the real power in a circuit in terms of impressed e.m.f.

17. Give the expression for the real power in a circuit in terms of effective e.m.f.

18. Give the expression for the apparent power in a circuit.

19. Explain what is meant by the "power factor" of a system. How is it found? Can it be found in any other way?

ALTERNATING CURRENTS

FORMULAS FOR "L" AND "X"; EXAMPLES

It will now be necessary to explain inductance in a somewhat more detailed manner. By definition a coil possesses an inductance of one henry when a current varying therein at the rate of one ampere per second causes one volt to be induced.

It will be easier to comprehend the meaning of this term if it is understood that **the henry is merely an algebraic expression for a particular size and shape of an electrical circuit.**

If Φ is the total flux produced in a coil and N the number of turns in the coil, then if that flux dies out in t seconds, the volts, E, induced will be:

$$E = \frac{\Phi N}{10^8 t}. \tag{1}$$

If L is the number of henrys possessed by a coil, in which one henry corresponds to the induction of one volt in a circuit when the current varies at the rate of one ampere per second, then if the coil carries a maximum current of I amperes and that current dies out in t seconds, the voltage E which will be induced therein is:

$$E = L \times \frac{I}{t}. \tag{2}$$

As formula 1 and formula 2 are both expressions for the voltage generated in a circuit, they may be combined as follows:

$$\frac{\Phi N}{10^8 t} = \frac{LI}{t}. \tag{3}$$

Multiplying both sides of this equation by t gives:

$$\frac{\Phi N}{10^8} = LI. \tag{4}$$

Transposing for the value of L gives:

$$\frac{\Phi N}{10^8 I} = L. \tag{5}$$

Now let Φ_a equal the flux produced per ampere of current and the formula is simplified to:

$$\frac{\Phi_a N}{10^8} = L. \tag{6}$$

In the ampere-turn formula for producing a given flux,

IN = the ampere-turns,
μ = permeability,
s = cross-section of core in square inches,
l = length of circuit in inches.

$$\frac{IN \times 3.192\,\mu s}{l} = \Phi. \tag{7}$$

The current, I, may be eliminated by substituting Φ_a for Φ and as the permeability, μ, for air, is one, the formula for the flux per ampere produced by a coil of a given number of turns with an air core is:

$$\Phi_a = \frac{N\,s \times 3.192}{l}. \tag{8}$$

Then substituting the value of Φ_a, formula 8, in formula 6 gives:

$$\frac{\dfrac{N\,s \times 3.192}{l}N}{10^8} = L. \tag{9}$$

from which the following will be obtained:

$$\frac{N^2\,s \times 3.192}{l \times 10^8} = L. \tag{10}$$

The above is the correct formula for the inductance in henrys of a coil with an air core provided the length is not great and the number of convolutions relatively few. If does not take account, however, of the mutual induction between the convolutions of the coil.

As an illustration of the application of this formula for the purpose of constructing a coil with a self-induction of one henry, let it be assumed that the length will be one inch and the diameter 20 inches. Transposing this formula for the value of N^2 will give:

$$\frac{10^8 \times l \times L}{3.192 \times s} = N^2.$$

Inserting these values:

$$\frac{100{,}000{,}000 \times 1 \times 1}{3.192 \times (20^2 \times 0.7854)} = 100{,}000 = N^2;$$

from which $N = \sqrt{100{,}000} = 316$ turns required.

The inductance in henrys varies from a few thousandths of a henry in a small coil like that of an electric bell to some hundreds of henrys in the field coil of a large generator.

The above formula may be applied to a coil having an iron core by the addition of the permeability of the iron:

Thus

$$L = \frac{N^2\, s\, \mu\, 3.192}{l \times 10^8}$$

As an illustration, consider the inductance of a reactance coil containing 300 turns wound about an iron core 6 inches long and possessing 12 square inches cross-sectional area. Assume the permeability of the iron to be 1,200.

$$\begin{aligned}
N &= 300 \text{ turns.}\\
\mu &= 1{,}200.\\
s &= 12 \text{ square inches.}\\
l &= 6 \text{ inches.}\\
L &= \frac{300^2 \times 12 \times 1{,}200 \times 3.192}{10^8 \times 6} = 6.9 \text{ henrys.}
\end{aligned}$$

Let it be assumed that the current in this coil changes from 6 amperes to 2 amperes in 0.5 second. What will be the average value of the voltage induced?

$$\text{Average } E = \text{henrys} \times \left(\frac{\text{change in amperes}}{\text{time to change}}\right) = L \times \frac{I}{t}$$

$$\frac{I}{t} = \frac{6-2}{0.5} = 6 \text{ amperes per second.}$$

$$\begin{aligned}
\text{Average } E &= L \times 6.\\
&= 6.9 \times 6.\\
&= 43.2 \text{ volts.}
\end{aligned}$$

The determination of the reactance of a circuit possessing a given inductance will next be considered:

If one henry, L, represents the induction of one volt in a circuit where the current varies at the rate of one ampere per second, then a current change of I amperes per second will produce IL volts. But the flux produced by the current in a coil cuts the convolutions of the coil four times for each cycle, that is, when the current is rising from zero to maximum in a positive direction it cuts all of the convolutions of the coil once. When it falls from maximum to zero it cuts them a second time. When it rises from zero to a negative maximum it cuts them a third time, and finally when it falls from a negative maximum to zero it cuts them a fourth time. If n equals the frequency of alternation in

cycles per second, the average voltage generated by the alternation of the current in a coil will be:

$$Avg.\ E = 4\,n\,L\,I.$$

As the

$$Avg.\ E = 0.636 \times Max.\ E \therefore 0.636 \times Max.\ E = 4\,n\,L\,I.$$

Dividing both sides of this equation by 0.636 gives

$$Max.\ E = 6.28\,n\,L\,I.$$

This expression may be reduced to ohms by dividing both sides by the current, I, in amperes. If resistance was being dealt with, the results would be resistance ohms, but as an inductive circuit is under consideration, the result is impedance ohms, which in this case are composed wholly of reactance ohms. Hence:

$$X = 6.28\,n\,L.$$

This expression states that the reactance ohms, X, encountered by the introduction of an alternating current into any inductive circuit varies directly as the product of the frequency, n, in cycles per second and the inductance, L, in henrys. It is equal to their product multiplied by 2π, which is 6.28. For a given inductance, then, the reactance encountered in ohms is directly proportional to the frequency of the alternating supply in cycles per second.

Now the **voltage induced** in any inductive circuit depends upon three things:

First: The current in the circuit.

Second: The frequency of supply.

Third: The inductance in the circuit.

Varying any of these factors varies the inductive e.m.f. in direct proportion.

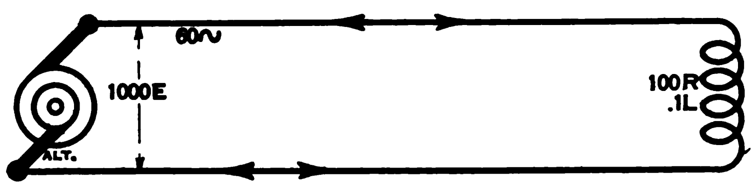


FIG. 536.

As an illustration of the effect of inductance in a circuit consider an alternator, Fig. 536, connected to a coil possessing

a resistance of 100 ohms and an inductance of one-tenth of a henry. The alternator delivers 1,000 volts and the frequency is 60 cycles. Required: the current in the coil and the power factor. An impedance triangle will first be constructed, Fig. 537. Here A-B represents the resistance and will be 100 units

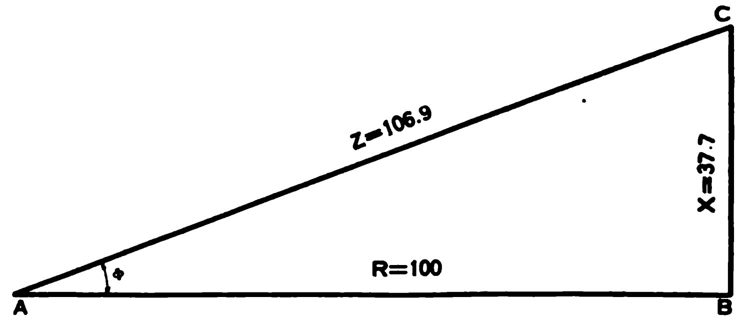


FIG. 537.

long. The reactance is equal to $6.28\ nL = 6.28 \times 60 \times 0.1 = 37.7$. B-C will therefore be plotted at right-angles to A-B, 37.7 units long. A-C will be the impedance,

$$Z = \sqrt{R^2 + X^2} = \sqrt{100^2 + 37.7^2} = 106.9 \text{ ohms.}$$

The current in this circuit will be:

$$I = \frac{E}{Z} = \frac{1000}{106.9} = 9.36 \text{ amperes.}$$

The effective e.m.f. which is actually engaged in forcing the current through the resistance of the circuit is, $IR = 9.36 \times 100 = 936$, effective E. The true power is, $I \times$ eff. E, $\therefore 9.36 \times 936 = 8{,}761$ watts. As $I \times$ Imp. E = volt-amperes and $I \times$ eff. E = watts, then

$$\frac{\text{Watts}}{\text{volt-amperes}} = \cos\Phi = \frac{9.36 \times 936}{1000 \times 9.36} = 0.936 = \cos\Phi.$$

By referring to a trigonometric table of sines and cosines the angle corresponding to the above value will be found to be 20° 40′.

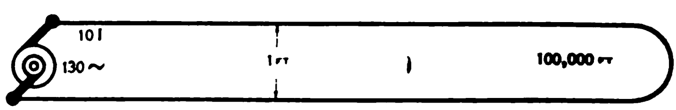


FIG. 538.

Next consider an alternating circuit having a total length of 100,000 feet, closed at the distant end, connected to an alternator furnishing a current of 10 amperes at a frequency of 130 cycles. The line consists of No. 4 copper and the distance between the wires is one foot. The resistance of the circuit is 25 ohms and the inductance is 0.0003 of a henry per 1,000 feet or 0.03 henry for the entire 100,000 feet. The circuit is pictured in Fig. 538. Let it be required to find the e.m.f. which the alternator must supply to maintain a current of 10 amperes in this circuit and the power factor of the system. The reactance, X, will be $6.28\,nL$. $6.28 \times 130 \times 0.03 = 24.5$ ohms reactance. Laying off A-B, in Fig. 539, 25 units long for the resistance and B-C, 24.5 units long for the reactance, the impedance, Z, will equal:

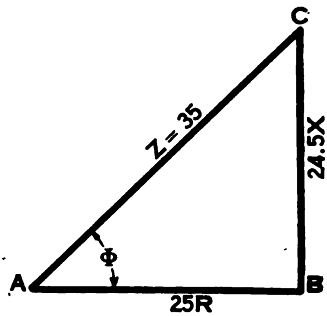


FIG. 539.

$$\sqrt{R^2 + X^2} = \sqrt{25^2 + 24.5^2} = 35 \text{ ohms.}$$

The voltage required to produce 10 amperes in this circuit will be:

$$IZ = E = 10 \times 35 = 350 \text{ volts.}$$

To produce 10 amperes in a direct-current circuit having a resistance of 25 ohms would require but 250 volts. Thus 100 additional volts are necessary in this circuit because of the reactance encountered.

$$\text{Cos } \Phi = \frac{R}{Z} = \frac{25}{35} = 0.715.$$

From a trigonometric table this will be found to correspond to an angle of 44° 25′.

The ratio of Z to R is 35 : 25, or 1.4 : 1. This is called the **impedance factor.** The impedance factor is the reciprocal of the power factor. It is the number by which the resistance of a circuit must be multiplied to get the impedance of a circuit. Tables are constructed which give the impedance factor for transmission lines of various sizes of wire with different spacing between the wires.

It will now be well to consider the most exaggerated case of inductance possible. A circuit doubled back upon itself such as a twisted lamp cord feeding an incandescent lamp has a minimum of inductance, for the amount of flux within the loop is negligibly small. The other extreme is found in the case of a coil of wire wound upon an iron core of large cross-section so that the coil is capable of developing the maximum possible flux.

Consider an alternator generating 1,000 volts with a frequency of 60 cycles and connected to such a coil possessing a resistance of 5 ohms and an inductance of 1 henry, represented in Fig. 540

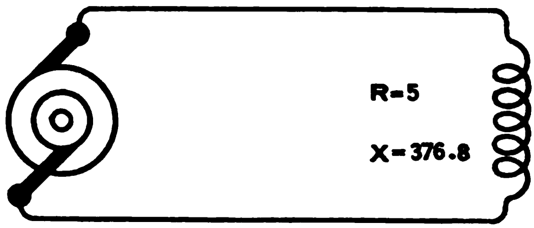


FIG. 540.

Required: The power factor, the apparent energy, the current and the true watts. The reactance will be:

$$6.28 \times n \times L = X = 6.28 \times 60 \times 1 = 376.8 \text{ ohms.}$$

The impedance triangle will now be plotted. Lay off A-B, Fig. 541, five units long, representing 5 ohms. Then at B erect the line B-C, representing the reactance 376.8 units long. The size of the page will not permit drawing this to scale. It will be much longer in fact than represented. The impedance is then A-C.

$$Z = \sqrt{R^2 + X^2} = \sqrt{5^2 + 376.8^2} = 377.8 \text{ ohms.}$$

The current will obviously be

$$I = \frac{E}{Z} = \frac{1000}{377.8} = 2.65 \text{ amperes.}$$

Cos Φ, obtained by the ratio of A-B to A-C, is

$$\frac{5}{377.8} = 0.013.$$

From a table this will be found to correspond to an angle of lag of 89° 15′.

The apparent energy will be the product of the current and the impressed volts,

$$2.65 \times 1{,}000 = 2{,}650 \text{ watts.}$$

The true energy equals $I \times E \times \cos \Phi$:

$$2.65 \times 1{,}000 \times 0.013 = 34 \text{ watts.}$$

In Fig. 537 the impedance 106.9 ohms was composed almost entirely of resistance which was 100 ohms, but in this case, Fig. 541, the impedance 377.8 is composed almost wholly of reactance, which is 376.8 ohms. In fact it will be observed that the resistance has very little effect upon the impedance here. The angle of lag is almost 90°. As it is impossible to have a coil without resistance, it is evident that the line *A-B* will have some length. Therefore *A-C* can never become parallel to *B-C*, and the angle of lag can never attain 90°. Its possible range, therefore, is from zero degrees to a maximum something short of 90 degrees.

This example is a striking illustration of the effect of a low power factor. Should there be one hundred such coils connected to an alternator they would call for 265 amperes at 1,000 volts, or 265,000 apparent watts. The actual power delivered by the station would be only 3,400 watts, but the current required to produce this output would be 265 amperes. The alternator's output would be 265 amperes and the windings would be heated as much as though this current was in phase with the voltage instead of nearly 90 degrees out of phase. The capacity of the alternator is limited to the actual carrying capacity of its armature conductors in amperes. The importance of high power factor in order that the kilo-volt-amperes may approach the real kilowatts, is therefore clearly apparent.

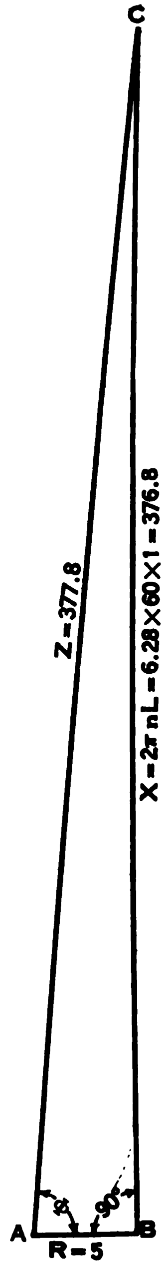


FIG. 541.—Effect of highly inductive circuit upon angle of lag.

In the preceding calculations it has been assumed that the power factor could be obtained from the expression

$$\frac{R}{Z} = \cos \Phi,$$

although it has also been stated that the power factor was

$$\frac{\text{Watts}}{\text{Volts} \times \text{amperes}}.$$

If there is iron in the core of a reactance coil the values obtained from these two expressions will not agree. This is because the impedance as calculated takes no account of whether the coil has an iron core or not. If an iron core is present the power as recorded on a wattmeter will be increased by the amount necessary to supply the core losses, consisting of eddy currents and hysteresis. Both of these losses will vary with the density; the hysteresis loss as the 1.6 power of the flux density and the eddy current loss as the square of the flux density. The correct power factor may be obtained for any device by measuring the watts input and the volt-amperes applied and then dividing the former by the latter. The expression

$$\frac{R}{Z} = \cos \Phi$$

will be a correct expression for the power-factor **only** in case the impedance under test has an air core.

SECTION XIV CHAPTER III

ALTERNATING CURRENTS

FORMULAS FOR "L" AND "X"; EXAMPLES

1. A coil 6 inches in diameter and 2 inches long contains 400 turns. It has an air core. What is its inductance in henrys?

2. A coil 2 inches in diameter and 10 inches long contains 400 turns of wire. The core is of iron with a permeability of 1,000. (*a*) What is its inductance? (*b*) What is its reactance on a 60-cycle circuit?

3. A coil 3 inches in diameter and 12 inches long contains 500 convolutions of wire. It has an iron core with a permeability of 1,200. (*a*) What is its inductance in henrys? (*b*) If a current of 5 amperes dies out in this coil in 0.5 second, what will be the voltage induced?

4. An alternator is connected to a circuit having a resistance of 20 ohms and an inductance of 0.1 henry. The frequency is 60 cycles per second. What must be the e.m.f. furnished by the alternator in order to set up a current of 10 amperes in the circuit?

5. If the maximum height of a sine wave of e.m.f. is 3,114 volts, what will the voltmeter register? If the maximum height of the current wave in the same case is 141 amperes, what will the ammeter register? If the power factor in this circuit is 83 per cent, what will the wattmeter register?

6. An electromagnet possesses an inductance of 0.05 henry and a resistance of 25 ohms. It is connected to a 108-volt, 60-cycle circuit.

(*a*) What is its reactance?

(*b*) What is its impedance?

(*c*) How many amperes does it get?

(*d*) What is the cosine of the angle of lag between the current and the impressed e.m.f.?

7. An alternator generating an e.m.f. of 1,000 volts at a frequency of 60 cycles per second, supplies current through a system, the resistance of which, is 100 ohms and the inductance 0.3 henry. Find the value of the current cosine of the angle of lag, power factor, apparent watts and true watts.

8. What is the "impedance factor" in an alternating current inductive circuit? Give formula and tabulate the meaning of each letter. What is the relation of the "impedance factor" to the "power factor"?

ALTERNATING CURRENTS

RESISTANCE AND REACTANCE, IN SERIES AND IN PARALLEL

The effect upon the angle of lag and current in a circuit caused by varying the resistance and reactance will now be considered. Assume a circuit consisting of X reactance and R resistance, connected in series as in Fig. 542. The resistance of X and the reactance of R are supposed to be negligible. Let the line A-B, Fig. 543, represent the resistance and B-C the reactance. Then A-C equals the impedance. Call this 35 ohms. Let an e.m.f. of 50 volts be impressed on this circuit, the current will obviously be:

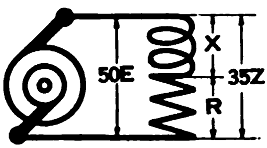


FIG. 542.—Circuit possessing resistance and magnetic reactance.

$$I = \frac{E}{Z} = \frac{50}{35} = 1.425 \text{ amperes.}$$

Allowing this current to flow, the energy component of the impressed voltage which is in phase with the resistance, is represented by the line A-G, while the reactance component which overcomes the inductance of the circuit is represented by the line G-D. Then the impressed 50 volts is represented by A-D, and the angle of lag is Φ.

Now suppose that the reactance, X, is increased as in Fig. 544, while the resistance R remains the same as before. The new impedance triangle will be A-B, resistance, as before, and B-C', reactance, from which the impedance, Z', will be A-C'. To overcome this impedance the voltage vector A-D will swing on the pivot A into the position A-D' where it is parallel with and opposed to the impedance, Z'. This increases the angle of lag from Φ to Φ'. The impressed voltage has not changed but the components into which it is resolved have been altered. Thus to overcome the reactance X' will now require F-D', inductive drop, while the resistance drop, which previously amounted to A-G, will now be reduced to A-F. The impedance has been increased to say 45 ohms and the current will be reduced thus

$$I \frac{E}{Z} = \frac{50}{45} = 1\ 11 \text{ amperes.}$$

Therefore, if in an inductive circuit the **reactance** is **increased** while the **resistance** is **not altered,** the **angle of lag increases** and the **current** flowing is **diminished.**

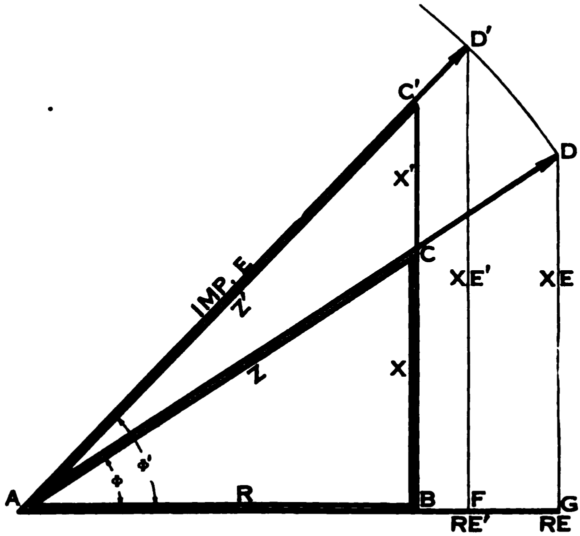


FIG. 543.—Vector diagram of conditions existing in Figs. 542 and 544.

X =reactance	XE =inductive drop
X' =reactance	XE' =inductive drop
R =resistance	RE =ohmic drop
Z =impedance	RE' =ohmic drop
Z' =impedance	

If in an inductive circuit, the *reactance, X,* is *increased* while the resistance, *R,* remains fixed, the *angle of lag, Φ, increases* and the *current, I, decreases.*

Next consider the effect of varying the resistance in a circuit while the reactance is kept fixed. In Fig. 545 let there be impressed, as before, 50 volts upon a circuit consisting of X ohms reactance and R ohms resistance in series. Let the combined impedance be 30 ohms. The current that will flow will be:

$$I = \frac{E}{Z} = \frac{50}{30} = 1.67 \text{ amperes.}$$

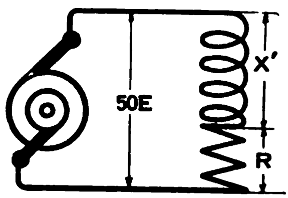


FIG. 544.—Additional reactance connected in circuit shown in Fig. 542.

Fig. 546 represents the vector, where A-R is the resistance, R-C the reactance and A-C the impedance. If a voltage A-D is

impressed on this circuit, it will be resolved into two components, A-G to overcome the resistance of the circuit, and G-D to overcome the reactance of the circuit. The angle of lag will be Φ. Next suppose that the circuit is altered by the addition of more resistance while the reactance remains the same, as in Fig. 547. The combined impedance will be increased as in the preceding example. The vector in Fig. 546 will now be A-B resistance and B-C' reactance, giving A-C' impedance. The voltage impressed now swings on the pivot A to the position A-D', where it is parallel to the impedance Z'. The resulting angle of lag diminishes from Φ to Φ', but as the impedance has increased from Z to Z', the actual current will fall, so if the impedance rises from 30 to 45 ohms the current will be

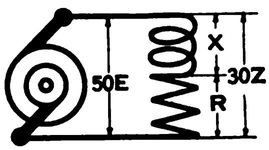


FIG. 545.—Circuit possessing resistance and reactance.

$$I = \frac{E}{Z} = \frac{50}{45} = 1.11 \text{ amperes.}$$

Therefore, if in an inductive circuit the **resistance** is **increased,** while the **reactance remains** the **same,** the **angle** of **lag decreases** and the **current diminishes.**

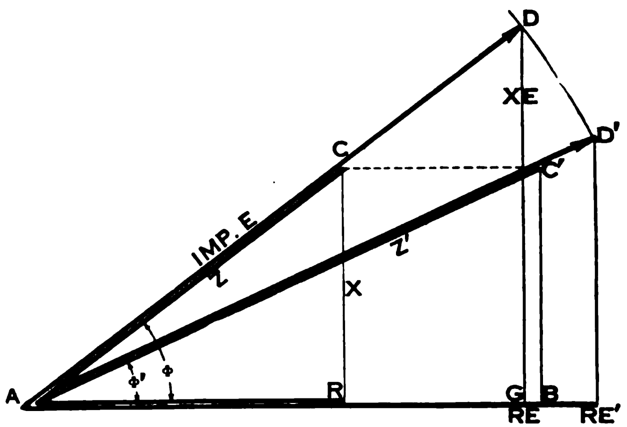


FIG. 546.—Vector diagram of conditions existing in Figs. 545 and 547.

X = reactance
R = resistance
R' = resistance
Z = impedance
Z' = impedance
XE = inductive drop
XE' = inductive drop
RE = ohmic drop
RE' = ohmic drop

If in an inductive circuit, the *resistance*, R, is *increased* while the reactance, X, remains fixed, *the angle of lag*, Φ, *decreases* and the *current*, I, *decreases.*

Thus in an inductive circuit, if the impedance is increased either through the addition of resistance or reactance, the result will be to decrease the current. If the increase is brought about through an increase in reactance, the angle of lag will **increase** and the power factor will fall; but if it is brought about through an increase in resistance the angle of lag will **decrease** and the power factor will improve.

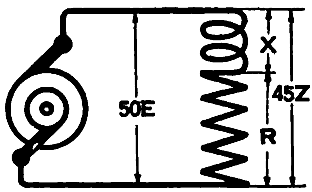


FIG. 547.—Additional resistance connected in circuit shown in Fig. 545.

The relation between the opposing forces in an inductive circuit and the e.m.fs. which overcome them should be kept clearly in mind. Thus, in Fig. 548, *A-B-C* represents an impedance triangle and the arrows indicate the direction of the various forces opposed to the voltage. The triangle *A'-B'-C'* represents the voltages in the circuit. The impressed voltage in direction *A'-C'* is applied to the impedance, *C-A*, which opposes it. This impressed voltage is resolved into two compo-

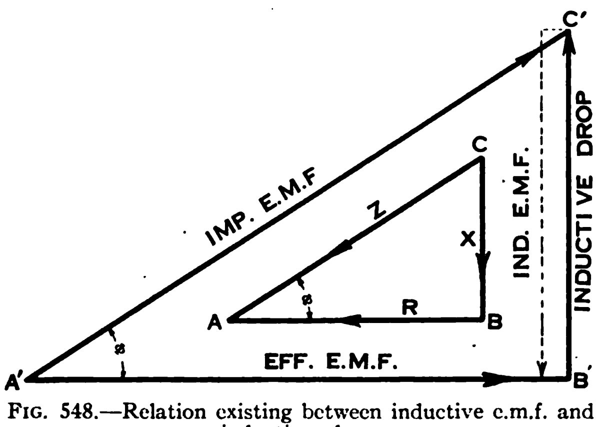


FIG. 548.—Relation existing between inductive e.m.f. and inductive drop.

nents, *A'-B'*, in phase with the current which it produces and in direct opposition to the resistance of the circuit, *B-A*. *B'-C'* is likewise a component of the impressed voltage which is called the "**inductive drop.**" This is exactly equal in magnitude but in direct opposition to the e.m.f. of self-induction, *C'-B'*. The reactance, *C-B*, is responsible for the inductive e.m.f. *C'-B'*.

These two forces are in the same direction and the reactive component of the impressed e.m.f., called the inductive drop, opposes them both.

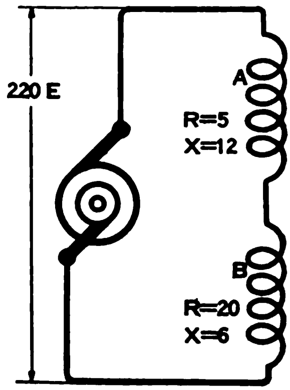


FIG. 549.—Alternator supplying two impedances in series.

It must be borne in mind that there are but two voltages in an inductive circuit, the impressed e.m.f., acting on the circuit, and the inductive e.m.f., more or less opposed thereto. For convenience in calculation, the impressed e.m.f. is supposed to be resolved into two components, one of which is employed to overcome the resistance of the circuit and the other to overcome the inductive e.m.f. encountered.

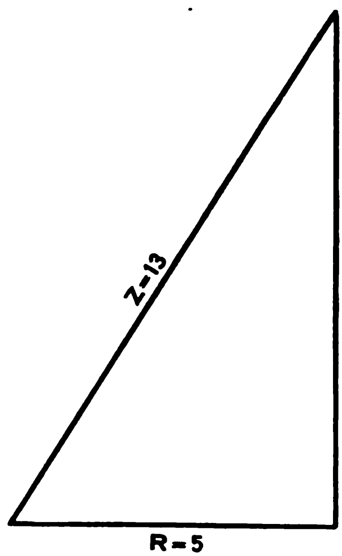


FIG. 550.—Vector diagram for impedance of A.

Calculation of Impedances in Series

The calculation of impedances in series will next be considered. Let an impedance, A, consisting of 5 ohms resistance and 12 ohms reactance, Fig. 549, be connected in series with an impedance, B, consisting of 20 ohms resistance and 6 ohms reactance, across a 220-volt alternator. The combined resistance of any number of separate resistances in series is equal to the sum of the separate resistances. The same rule holds good **for the impedances in series** except that **the summation must be made geometrically.** The impedance of A is:

$$Z = \sqrt{R^2 + X^2} = \sqrt{5^2 + 12^2} = 13 \text{ ohms.}$$

Fig. 550 shows the vector for this impedance.

The impedance of B is:

$$Z = \sqrt{R^2 + X^2} = \sqrt{20^2 + 6^2} = 20.9 \text{ ohms.}$$

The vector for this is shown in Fig. 551. The vector for the combined impedance of these two in series is shown in Fig. 552. It is not the sum of *A-D*, 13 ohms, plus *D-C*, 20.9 ohms, as might be supposed, for these two impedances differ in phase by the angle θ. The resistance components of the two impedances, *A-E*

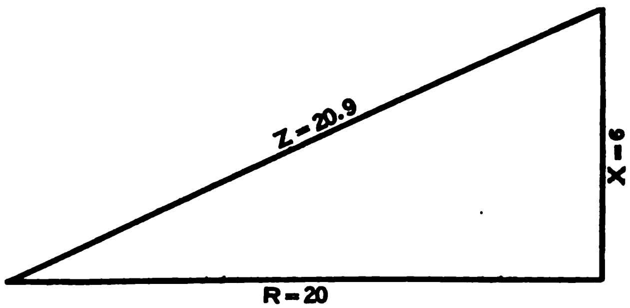


FIG. 551.—Vector diagram for impedance of *B*.

and *D-F*, are in phase and may therefore be added arithmetically. The reactance components *E-D* and *F-C* are likewise in phase with each other and may be added arithmetically. Therefore the combined impedance is

$$Z'' = \sqrt{(R + R')^2 + (X + X')^2} = \sqrt{(5 + 20)^2 + (12 + 6)^2} = 30.85 \text{ ohms.}$$

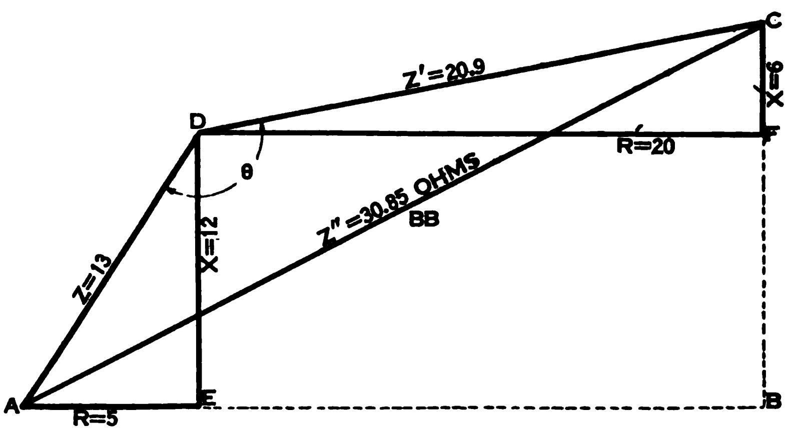


FIG. 552.—Vector diagram showing summation of two impedances in series.

This process may be extended indefinitely for any number of impedances in series. Thus, if four impedances, *A-B-C-D*, Fig.

553, are connected in series, each having its own particular resistance and reactance, the combined impedance Z of the entire series is not the arithmetical sum of the separate vectors

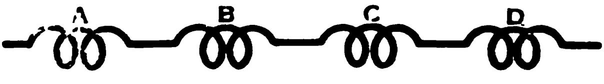


FIG. 553.—Illustrating any number of impedances in series.

A-B-C-D, in Fig. 554, but is the square root of the squared sum of $[R + R' + R'' + R''']$ and $[X + X' + X'' + X''']$. That is, the total impedance is E-G, which is $\sqrt{(E\text{-}F)^2 + (F\text{-}G)^2}$.

In the example shown in Fig. 552, the current will be:

$$I = \frac{E}{Z} = \frac{220}{30.85} = 7.1 \text{ amperes.}$$

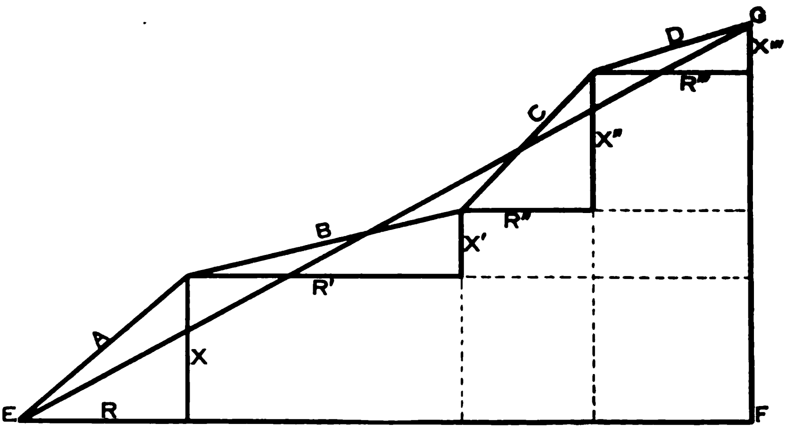


FIG. 554.—Vector diagram illustrating method of summation of any number of impedances in series.

The power factor will be:

$$\text{Cos } \Phi = \frac{R}{Z} = \frac{25}{30.85} = 0.81 = \cos \Phi. \quad \text{Power factor} = 81\%.$$

The voltage across A will be:

$$IZ = 7.1 \times 13 = 92.3 \text{ volts.}$$

The voltage across B will be:

$$IZ = 7.1 \times 20.9 = 148.4 \text{ volts.}$$

The arithmetical sum of these two voltages would be 240.7 but the geometric sum is only 220. This will be made clear from an inspection of Fig. 555, where *A-C* represents the voltage impressed upon the two devices. The voltage on *A* is 92.3 while the voltage on *B* is 148.4, but because of the angle, θ, which exists between them, 220 volts will supply both of these separate e.m.fs. in series. That is, their geometric sum is less than their arithmetical sum because the two e.m.fs. required do not have their maximum values at the same instant.

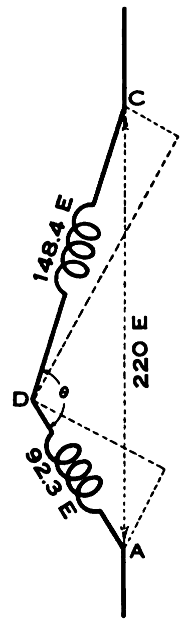


FIG. 555.—Illustration showing the relative phase relation between the e.m.fs. across various impedances in series, with respect to the line e.m.f.

A practical method of ascertaining the inductance possessed by a given coil is as follows: Let an alternating source *G*, Fig. 556, be connected to the coil *X* to be measured. An ammeter, *A*, shows the current and a voltmeter, *V*, the drop across the coil. A rheostat *R* limits the current. The impedance will be the voltmeter reading divided by the ammeter reading:

$$\frac{V}{A} = Z.$$

The coil should now be transferred to a direct current circuit, Fig. 557, with a rheostat R' in series to limit the current. The drop across the coil, as measured on the voltmeter divided by the current, will now give the resistance. Thus,

$$\frac{V'}{A'} = R.$$

The impedance $Z = \sqrt{R^2 + X^2}$, therefore $X = \sqrt{Z^2 - R^2}$; but $X = 6.28\, n\, L$. Therefore

$$L = \frac{X}{6.28n}.$$

This gives the inductance for the coil as it stands while under test whether with or without an iron core. This **inductance** is based upon its **reactance** which in turn is governed by the **frequency.** It must be observed, however, that the **inductance** is **independent** of the **frequency.** The frequency enters into the calculation only as a factor of the reactance.

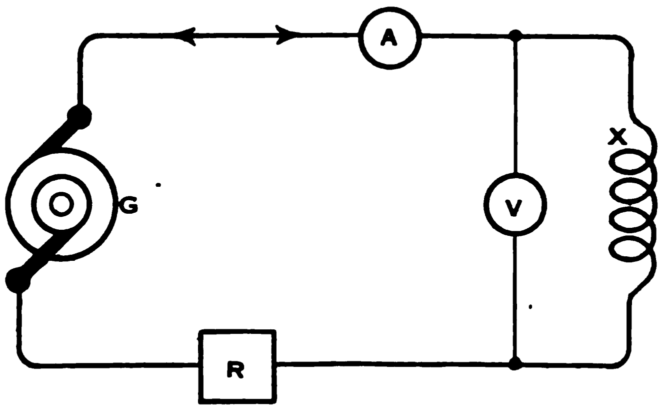


FIG. 556.—Connections for taking data from which the impedance in circuit may be computed.

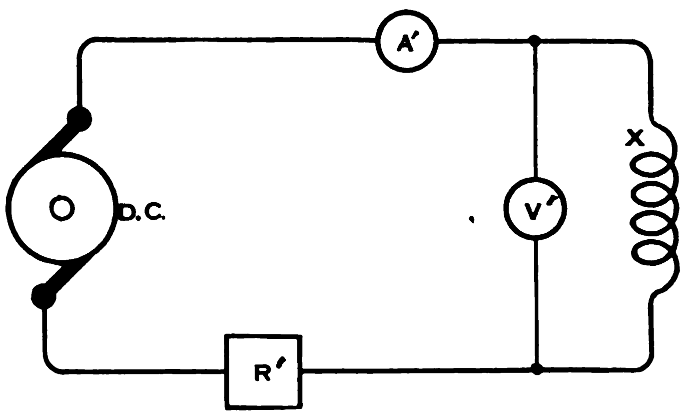


FIG. 557.—Connections for taking data from which the resistance in circuit may be computed.

Calculation of Impedances in Parallel

In considering impedances in parallel, it will be remembered that the combined resistance of any number of resistances in multiple is the reciprocal of the sum of the reciprocals of the separate resistances. The same rule may be applied for impedances in parallel except that the summation must be made geometrically.

Therefore the combined impedance of any number of separate impedances in parallel is the reciprocal of the geometric sum of the reciprocals of the separate impedances.

Take a non-inductive resistance of 100 ohms, A, Fig. 558, in parallel with a magnetic reactance, B, having 5 ohms resistance

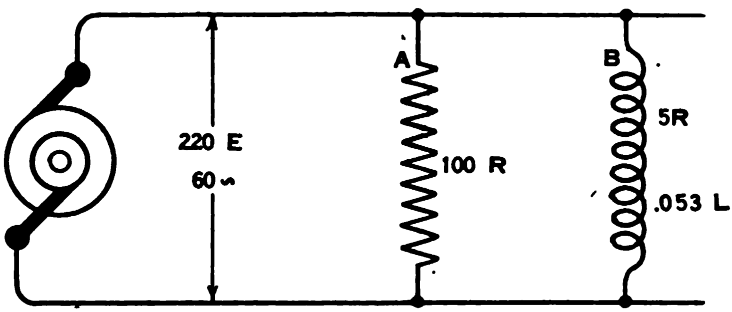


FIG. 558.—Method of combining impedances in parallel.

and 0.053 henry inductance. Let them be connected across a 220-volt, 60-cycle source. Required, the combined impedance; the current and the power factor.

The reactance X of B is $6.28\,nL = 6.28 \times 60 \times 0.053 = 20$ ohms.

The impedance, Z_x, of B is:

$$Z_x = \sqrt{R^2 + X^2} = \sqrt{5^2 + 20^2} = 20.6 \text{ ohms.}$$

The reciprocal of A is

$$\frac{1}{R} = \frac{1}{100} = 0.01.$$

The reciprocal of B is

$$\frac{1}{Z_x} = \frac{1}{20.6} = 0.048.$$

Fig. 559 shows the impedance triangle for B. The reciprocal of A will be represented by a straight line, C-D, Fig. 560, 0.01 unit long.

The reciprocal triangle for B is constructed in the following manner: First lay off E-F, Fig. 560, equal to 0.048 unit long

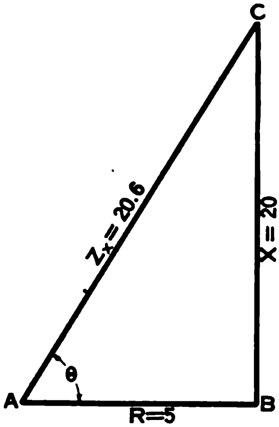


FIG. 559.—Vector diagram for impedance of circuit B.

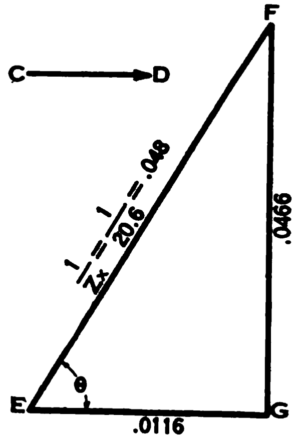


FIG. 560.—Vectors showing reciprocals of impedances A and B.

with the angle θ from Fig. 559, preserved between E-F and E-G. Then:

$$\cos\theta = \frac{R}{Z_x} = \frac{5}{20.6} = 0.2427.$$

$$\sin\theta = \frac{X}{Z_x} = \frac{20}{20.6} = 0.9708, \text{ from which therefore:}$$

$$\begin{aligned} E\text{-}G &= E\text{-}F \times \cos\theta \\ &= 0.048 \times 0.2427 = 0.0116, \text{ and} \\ G\text{-}F &= E\text{-}F \times \sin\theta \\ &= 0.048 \times 0.9708 = 0.0466. \end{aligned}$$

Thus the length of the line E-G is found to be 0.0116 and the length of the line G-F, 0.0466. This is called the reciprocal triangle. The line E-F is truly the reciprocal of the impedance in Fig. 559. The angles θ are the same in Fig. 559 and Fig. 560, but the line E-G is not the reciprocal of the resistance component A-B, Fig. 559, neither is the line G-F the reciprocal of the reactive component B-C. It is not proper that they should be. It

is only necessary that the angle θ be preserved in both the impedance triangle and the reciprocal triangle and that the angle at G shall be a right angle as at B. These conditions are assured by the above procedure.

The two reciprocals thus obtained must now be combined. In Fig. 561 the reciprocal of the resistance of branch A, C-D, is

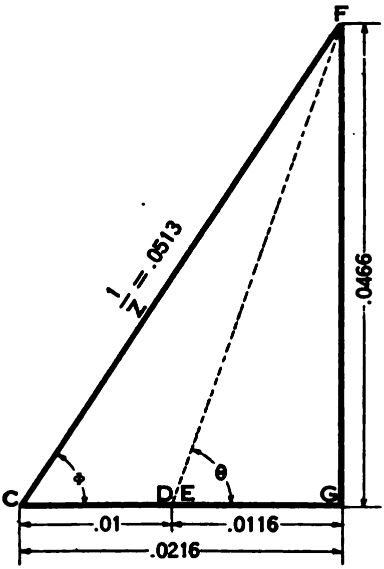


FIG. 561.—Method of combining reciprocal vectors.

added to the energy component of the reciprocal triangle of branch B, E-G. Perpendicular thereto at the point G, is erected the reciprocal component G-F, 0.0466 unit long. The geometric sum of these reciprocals will therefore be:

$$\frac{1}{Z} = \sqrt{0.0216^2 + 0.0466^2} = 0.0513.$$

The reciprocal of the geometric sum of the reciprocals will be:

$$Z = \frac{1}{0.0513} = 19.5 \text{ ohms.}$$

The current in the line will be:

$$I = \frac{E}{Z} = \frac{220}{19.5} = 11.2 \text{ amperes.}$$

But the current in A will be:

$$I = \frac{E}{R} = \frac{220}{100} = 2.2 \text{ amperes.}$$

The current in B will be:

$$I = \frac{E}{Z_x} = \frac{220}{20.6} = 10.68 \text{ amperes.}$$

The arithmetical sum of these currents will be 12.88 amperes: but because of the phase angle between them the line current supplying the two will only be 11.2 amperes as shown. The power factor for the two combined circuits will be

$$\text{Cos } \Phi = \frac{CG}{CF} = \frac{0.0216}{0.0513} = 0.421,$$

or a power factor of 42.1%, which corresponds to the angle Φ in Fig. 561.

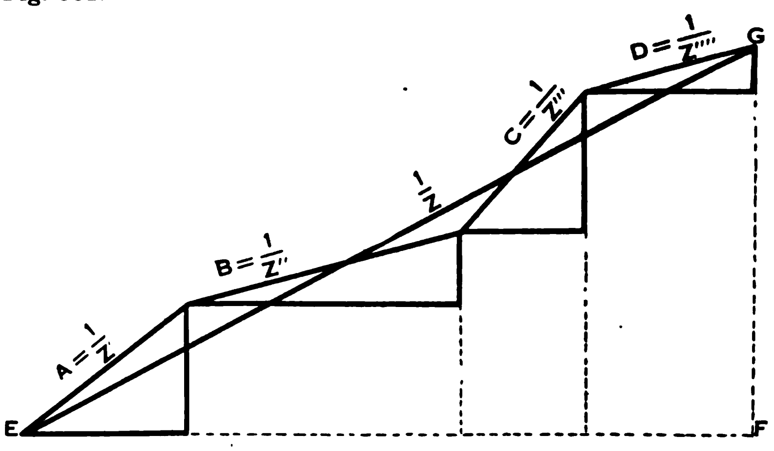


FIG. 562.—Vector diagram showing summation of reciprocal vectors of any number of impedances in parallel.

In series circuits there was a displacement in phase of the various voltages across the different devices in series, resulting in a total voltage less than the arithmetical sum depending on the various phase angles. The **currents in all the devices** in a **series** circuit were **in phase** but the **voltages** across the various devices **differed** in phase, hence **each device had a separate**

power factor, while the **system as a whole** had a **resultant power factor.**

With impedances in parallel, the **phases** of the **currents** in the various branches **differ** so that the total current required is less than the arithmetical sum of the currents in the various branches. But the **voltages** across the various devices **in**

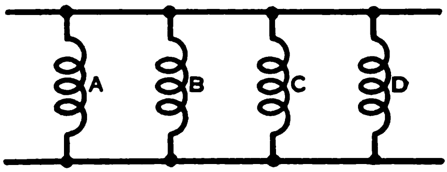


FIG. 563.—Showing any number of impedances in parallel.

multiple are **in phase.** As the **currents** in the various branches differ in phase **each branch** will have a **separate power factor** while the **system as a whole** has a **resultant power factor.**

In the example just considered the power factor of branch A is 100% while the power factor of branch B is

$$\frac{R}{Z_x} = \frac{5}{20.6} = 0.2427 = \text{power factor, } 24.2\%.$$

Any number of impedances in parallel may be similarly combined. Thus, if in Fig. 562 the various triangles A-B-C-D represent the reciprocals of the impedances of branches A-B-C-D, in Fig. 563, then the line E-G, $\frac{1}{Z}$, represents the geometric sum of the reciprocals of the separate impedances, and the reciprocal of this sum, or $\frac{Z}{1}$, represents the combined impedance.

SECTION XIV CHAPTER IV

ALTERNATING CURRENTS

RESISTANCE AND REACTANCE IN SERIES AND IN PARALLEL

1. If, in an inductive circuit, the reactance is increased while the resistance is not altered, what is the effect upon the angle of lag and the current? Sketch vectors illustrating.

2. If, in an inductive circuit, the resistance is increased while the reactance remains the same, what will be the effect upon the angle of lag and current? Sketch vectors illustrating.

3. Give formula for the combined impedance of two impedances (each consisting of reactance and resistance) in series.

4. A coil possessing 5 ohms resistance and 4 ohms reactance is in series with a coil of 6 ohms resistance and 3 ohms reactance. What is their combined impedance?

5. A coil possessing 10 ohms resistance and 8 ohms reactance is connected in series with a coil of 25 ohms resistance and 12 ohms reactance. What voltage will be required to force 5 amperes through the circuit?

6. Three magnetic reactances, *A*, *B*, and *C*, are connected in series on a 220-volt circuit. *A* possesses 10 ohms resistance and 15 ohms reactance. *B* possesses 18 ohms resistance and 12 ohms reactance. *C* possesses 30 ohms resistance and 40 ohms reactance.

   (*a*) What is the combined impedance?
   (*b*) What is the power factor of the circuit?
   (*c*) What is the current flowing?
   (*d*) What is the apparent power?
   (*e*) What is the true power?
   (*f*) What is the impedance factor?

7. An inductance coil has an impedance of 60 ohms on a 60-cycle circuit. Its resistance is 15 ohms. What is its inductance in henrys?

8. Two impedances, *A* and *B*, are connected in parallel, on a 440-volt, 60-cycle circuit. *A* has a resistance of 50 ohms and an inductance of 0.02 henry. *B* has a resistance of 80 ohms and an inductance of 0.06 henry.

   (*a*) What is the combined impedance of *A* and *B*?
   (*b*) What is the power factor?
   (*c*) What is the current?
   (*d*) What is the apparent energy?
   (*e*) What is the real energy?

9. Three impedances, *A*, *B*, and *C*, are connected in parallel on a 60-cycle circuit. *A* has 200 ohms resistance. *B* has 60 ohms resistance and an inductance of 0.04 henry. *C* has 40 ohms resistance and an inductance of 0.5 henry.

   (*a*) What is the combined impedance?
   (*b*) What is the power factor?
   (*c*) What is the current in each branch at 110 volts?
   (*d*) What is the combined current in all three branches at 110 volts?

ALTERNATING CURRENTS

THE EFFECT OF CAPACITY IN A CIRCUIT

Every electrical circuit possesses more or less electrostatic capacity. That is, it is capable of storing up energy in the form of electrostatic stress and if the applied e.m.f. is removed the energy so stored may be returned to the circuit.

The conditions for the establishment of capacity in a circuit are, two parallel conductors connected to a source of potential, the conductors being insulated from one another. These conductors correspond to the plates of a condenser. The insulating medium, whether it be a solid or merely air, forms the dielectric. Consider a battery, *B*, Fig. 564, connected to

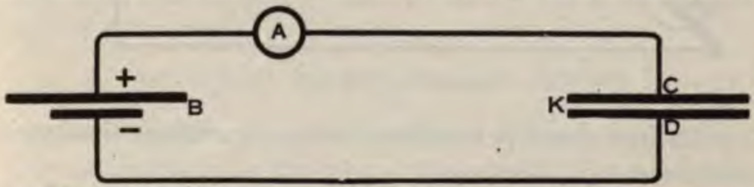


FIG. 564.—Surge of current from battery charging condenser.

a condenser, *K*, consisting of two plates of tin foil separated by a dielectric. An ammeter, *A*, connected in series indicates the current. At the moment the circuit is closed current will flow from *B* through *A* into the condenser at *C*. Current will likewise flow out of the condenser at *D* and back to the battery. At the moment the circuit is first closed the flow of current will be a maximum but as the condenser becomes filled, that is, charged, its potential difference rises and it develops a counter e.m.f. The current thus tapers off, the ammeter showing the decreasing value until finally the current ceases to flow and the ammeter indicates zero. At this time the potential difference between *C* and *D* is equal and opposite to the e.m.f. of the battery *B*. If, now, the battery is disconnected and the wires *C-D* are connected to each other, the energy stored in the condenser is given back into the circuit, establishing in its reaction a reverse flow of current, the total quantity of the discharge being approximately equal to the amount of charge from the battery.

Inductance in an electrical circuit corresponds to **inertia** in mechanics. **Capacity** in an electrical circuit corresponds to **elasticity.** Inductance in a circuit absorbs energy during one part of the cycle and restores it to the circuit during another part of the cycle. Little or no energy is wasted. Capacity in a circuit involves the storing of energy during one part of the cycle which in turn is restored to the circuit during another part of the cycle. Little or no energy is wasted.

The inertia of a fly wheel corresponds to inductance in a circuit. The elasticity of a spring corresponds to capacity in a circuit. The **inductive e.m.f.** is generated in a circuit when the **current changes** in value. The **e.m.f.** due to **electrostatic**

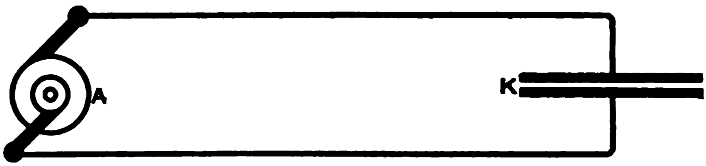


FIG. 565.—Alternator connected to condenser.

capacity in a circuit is manifested when the **voltage changes** in value.

The capacity of a condenser is the quantity of energy which it can store in the form of electrostatic strains. It is proportional to three things: The area of the plates, the e.m.f. producing the strain, and the dielectric power of the insulating medium separating the plates.

A condenser has a capacity of one farad, C, when one ampere flowing into it for one second will charge it to a potential of one volt. Or the capacity of a condenser, C, is the quantity of electricity in coulombs Q it will store up per volt of pressure applied. Thus:

$$\frac{Q}{E} = C, \text{ and } Q = C \times E, \text{ where } E = \text{e.m.f. in volts.} \qquad (1)$$

In an alternating circuit containing capacity the current charges and discharges the condenser four times in each cycle. Thus, if an alternator, A, in Fig. 565, sends a wave of current in a positive direction to the condenser K, the condenser is thereby charged. When this current dies out the condenser discharges. When the current reverses and surges through the

line in a negative direction, the charge is in the reverse direction, and when it falls from a negative maximum to zero the con-

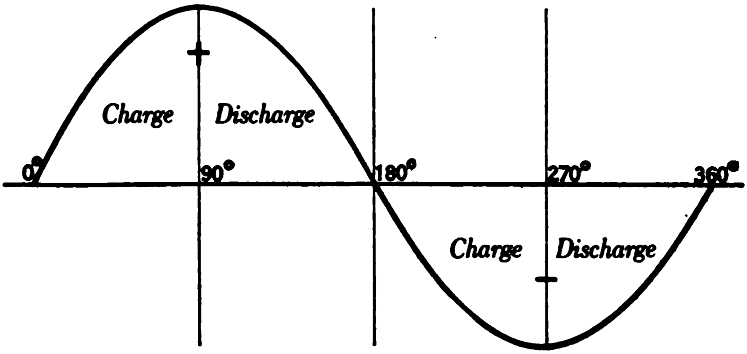


FIG. 566.—Various current waves during one cycle from alternator.

denser again discharges, Fig. 566. Therefore the time for each charge or discharge is

$$t = \frac{1}{4n} \tag{2}$$

t being the seconds and n the frequency in cycles per second.

Due to the change in the value of the current from maximum to zero during each change, the total quantity Q which will flow

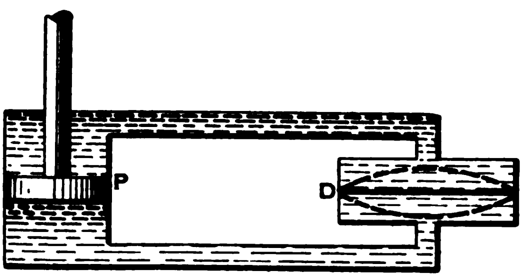


FIG. 567.—Mechanical analogy illustrating how current can apparently flow through a condenser.

into a condenser is equal to the average rate of flow I, multiplied by the time of flow.

$$\text{Average } I \times t = Q \tag{3}$$

Such a condition of current flow into and out of a condenser may be studied from Fig. 567. Here the piston of the pump, P, is supposed to alternate its direction and move the water in

the circuit to and fro in the pipes leading to D. Let D have a flexible diaphram of rubber, perfectly tight so that it will not permit any water to pass through it yet sufficiently flexible to yield under the pressure from either side. If, now, the piston, P, of the pump is moved up and down the water will flow back and forth through the two pipe lines and the diaphram D will take the convex positions shown by the dotted lines, alternately moving downward and upward. Thus, while no water actually passes through D it flows in first on one side and out on the other and then the direction of flow is reversed. The actual volume of flow will be determined by the size and the elasticity of the diaphram. This would correspond to the capacity of the condenser.

As stated above, Q equals the average rate of flow multiplied by the time of flow. Combining formulas 2 and 3, gives

$$Q = \text{Avg.}\ I \times \frac{1}{4\ n} = \frac{\text{Avg.}\ I}{4\ n}. \tag{4}$$

Now combining equations 1 and 4, gives

$$CE = \frac{\text{Avg.}\ I}{4\ n} \quad (5) \qquad \therefore \qquad E = \frac{\text{Avg.}\ I}{4\ n\ C} \quad (6)$$

$$\text{Avg.}\ I = 0.636 \times \text{Max.}\ I \tag{7}$$

$$E = \frac{0.636\ \text{Max.}\ I}{4\ n\ C} = \frac{\text{Max.}\ I}{6.28\ n\ C} \tag{8}$$

Dividing both sides by I to reduce to ohms,

$$\frac{E}{I} = \frac{\dfrac{\text{Max.}\ I}{6.28\ n\ C}}{I} = \frac{\text{Max.}\ I}{6.28\ n\ C} \times \frac{1}{I} = \frac{1}{6.28\ n\ C}. \tag{9}$$

Therefore

$$\frac{1}{6.28\ n\ C} = \text{ohms, } \textbf{capacity reactance}\ (Y)$$

Since most calculations involve microfarads instead of farads, it is usual to write this equation as follows:

$$\frac{1{,}000{,}000}{6.28\ n\ M.F.} = Y \text{ ohms.} \tag{10}$$

As $I = \frac{E}{Z}$; when $Z = Y$, as in a condenser:

$$I = \frac{E}{\frac{1}{6.28nC}} \qquad (11)$$

or

$$I = 6.28\, nCE \qquad (12)$$

or

$$I = \frac{6.28\ n\ M.F.,\ E}{1{,}000{,}000} \qquad (13)$$

A study of formula 12 will show that the current which will flow to and fro between an alternator and a condenser and which to all intents and purposes flows through it, is proportional to three things:

First: n, the frequency in cycles per second.

Second: C, the capacity in farads.

Third: E, the e.m.f. in volts applied.

Varying any of these quantities varies the rate of flow in direct proportion.

As an illustration of the operation of this law, consider Fig. 568. Here a condenser, K, of 2 microfarads capacity is connected to an alternator delivering 2,000 volts at a frequency of 130

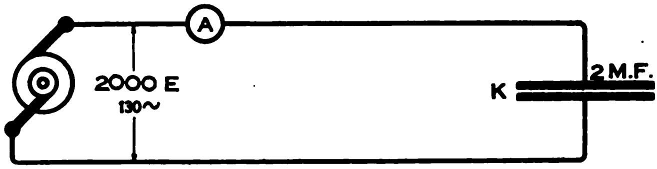


FIG. 568.—Actual current flowing in circuit between alternator and condenser.

cycles. Required the current and the capacity reactance of the condenser. Applying formula 12: $I = 6.28 \times 130 \times 0.000{,}002 \times 2{,}000 = 3.26$ amperes. The capacity reactance Y will be:

$$Y = \frac{E}{I} = \frac{2000}{3.26} = 613 \text{ ohms.}$$

The condenser K has its coatings insulated from each other by a resistance of several millions of ohms. Yet it behaves as if it had an actual resistance of only 613 ohms, for it apparently passes a current of 3.26 amperes under a pressure of 2,000 volts.

Now consider the relation which the e.m.f. of the condenser bears to the charging current. It has already been pointed out that in an inductive circuit the induced e.m.f. lags 90° behind the current, whose variations produce it, as shown at *H-G* in Fig. 569. Referring to Fig. 564, when the battery is first connected to the condenser, the flow of the current will be a

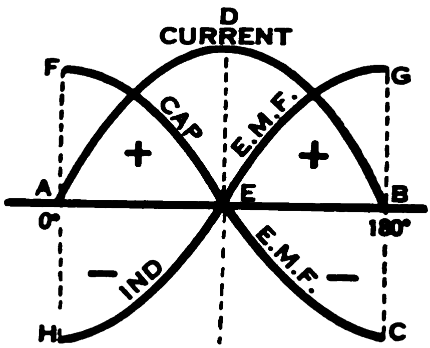


FIG. 569.—Comparative phase angles between capacity e.m.f., inductive e.m.f. and current in an A. C. circuit.

maximum at the instant the e.m.f. is applied, because the e.m.f. of the condenser is zero, but it rapidly falls off so that in a small fraction of a second the current practically ceases to flow entirely and the condenser is charged. The e.m.f. of the condenser reaches a maximum when the charging current reaches zero. The condenser behaves as though it had acquired a counter e.m.f. tending to keep out the current and this counter e.m.f. gradually increases until, when the condenser is charged, its voltage is equal and opposite to that of the battery. If the condenser is disconnected from the battery and the plates connected by a wire, a reverse charge will flow for a short time. It will be observed that this current is a maximum when the terminals are first connected. Now as the flow of current into the condenser is a maximum at the start when the condenser's e.m.f. is zero, and as the flow of current into the condenser is zero when the counter e.m.f. is a maximum, it follows that a wave representing the e.m.f. of the condenser must be 90° away from the current.

It must now be determined whether this e.m.f. is 90° ahead of, or behind the current. When the current is flowing into the

condenser the counter e.m.f. is constantly increasing in such a direction as to keep it out. At the moment when the current ceases to flow into the condenser in a positive direction, as at *B*, Fig. 569, the e.m.f. of the condenser tending to discharge it is a maximum *C*, in the opposite direction. The point of maximum condenser e.m.f. in a negative direction must therefore coincide with the termination of the flow of current into it in a positive direction so that as the current changes sign at *B*, it has behind it the full thrust of the e.m.f. of the discharging condenser at *C*. Thus during the interval while the current is falling from *D* to *B*, the counter e.m.f. of the condenser must be increasing in the opposite direction from *E* to *C*. It must therefore be

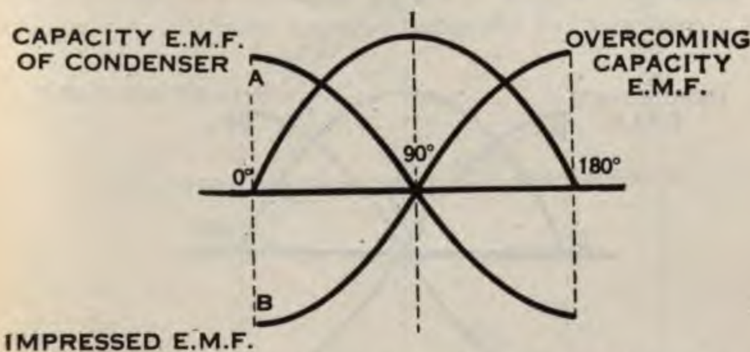


FIG. 570.—Showing the relation between the e.m.f. applied to a condenser and the e.m.f. of the condenser itself.

represented by the curve *F-E-C*, which is 90° ahead of the current. That is, it reaches its maximum in a positive direction, *F*, 90° earlier in the cycle than the current reaches its maximum in the same direction at the point *D*.

A distinction should be made between the capacity e.m.f. of a condenser and the impressed e.m.f. of the line applied to the condenser. In Fig. 570 an alternation of current, *I*, is shown. As has already been stated, the capacity e.m.f. of the condenser reaches its maximum at the point *A*, 90° in advance of the current. The impressed e.m.f. of the line on the condenser is diametrically opposed thereto (neglecting losses in the condenser), and is represented by the curve *B*. This e.m.f. in a circuit containing only **capacity** reaches its maximum 90° later

than the current; therefore the **current leads** the **impressed e.m.f.** by 90°.

The corresponding conditions for magnetic reactance in a circuit are shown in Fig. 571. Here an alternation of current, *I*, is shown. The inductive e.m.f., *X*, reaches its maximum 90° later than the current as has already been explained. Diametrically opposed thereto is the impressed e.m.f., *B*. Assuming the entire impressed e.m.f. to be employed in overcoming the inductance, as when there are no losses in the coil, this impressed voltage is diametrically opposed to the inductive and is therefore 180° away from it in phase. Thus the **current** in a purely **inductive** circuit is 90° **behind** the **impressed e.m.f.**

From the foregoing it will be seen that the capacity e.m.f. of a condenser and the inductive e.m.f. generated in a coil are

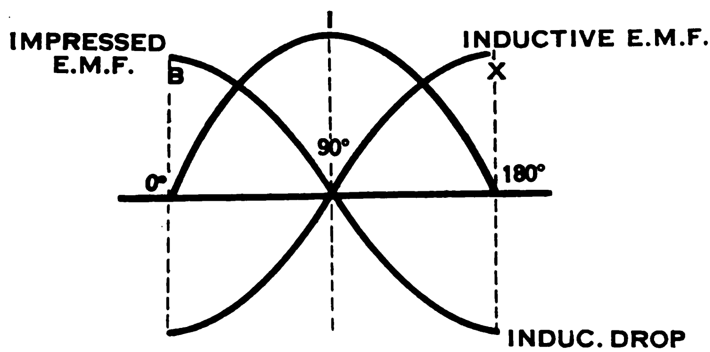


FIG. 571.—Showing the relation between the voltage applied to a magnetic reactance and the inductive e.m.f. generated therein.

180° apart in phase from each other and therefore in exact opposition. As these two e.m.fs. are always opposing each other, when one is **retarding** the current the other is aiding it, and vice versa. Thus in Fig. 569, while the current is rising from *A* to *D* in a positive direction, the inductive e.m.f. from *H* to *E* in a negative direction is opposing its rise, but the capacity e.m.f. from *F* to *E* is aiding its rise. While the current is falling from *D* to *B*, the induced e.m.f. from *E* to *G* is aiding the current and trying to maintain it, but the capacity e.m.f. during this interval from *E* to *C* is opposing the current.

The e.m.f. of the condenser has no effect on the total energy

of the circuit for the same reason that held good in regard to the inductive e.m.f. A condenser in a system resembles a spring alternately receiving and giving up energy but absorbing practically none.

Capacity reactance in a circuit may be considered as the exact opposite of magnetic reactance. If, as pictured in Fig. 569, the capacity e.m.f., *F-A*, is exactly equal in magnitude to the inductive e.m.f., *B-G*, the net effect upon the circuit is as

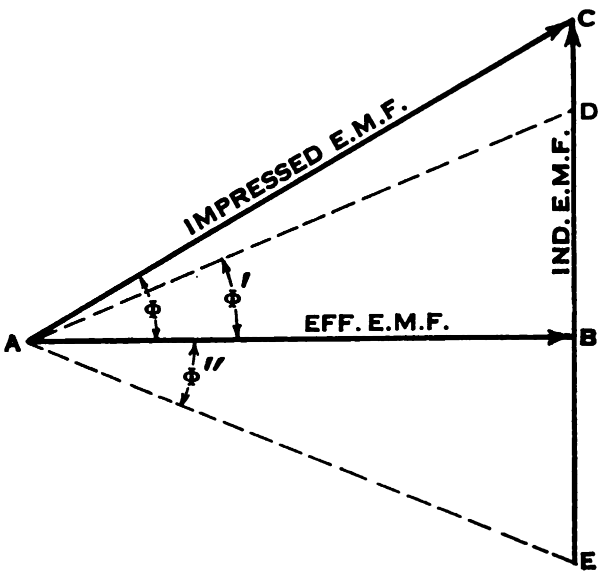


FIG. 572.—The effect upon the angle of lag brought about by the introduction of capacity in a circuit already possessing inductance.

if neither capacity reactance nor magnetic reactance were encountered. The impressed e.m.f. will then be only that necessary to overcome the resistance of the circuit. That is, it will be equal to the effective e.m.f., and there will be no angle of lag and the circuit will act as if it possessed resistance only. Fig. 572 illustrates the effect of varying amounts of capacity reactance in a circuit. In the triangle *A-B-C*, *A-B* is the effective e.m.f. overcoming the resistance of the circuit and *B-C* is the inductive drop overcoming the magnetic reactance of the circuit. If capacity reactance is added to this circuit, its effect will be to

neutralize more or less of the inductive e.m.f., thus the capacity effect reckoned downward from C to D would reduce the combined effect of the capacity and inductance to B-D. The impressed e.m.f. to deliver the same current will now become A-D, and the angle of lag would fall from Φ to Φ'. If the capacity e.m.f. were sufficient to equal C-B it would then entirely neutralize the inductive e.m.f. B-C. The impressed e.m.f. required would then be simply A-B and the angle of lag would disappear entirely. If still more capacity reactance were introduced in the circuit, causing a capacity e.m.f. equal in amount to C-E, it would then exceed the inductive e.m.f., B-C, by the amount B-E. The impressed e.m.f. would now be A-E. Instead of an angle of lag the angle Φ'' will appear as an angle of lead. That is, the current will be in the direction A-B while the impressed e.m.f., A-E, will be behind the current by the angle Φ''.

Inductance in a circuit by itself is **objectionable. Capacity** in a circuit by itself is **objectionable,** but **if one** only **exists** in a system the **addition of** the **other** will result in an **improvement** in the power factor.

The current in an alternating circuit is

$$I = \frac{E}{Z}.$$

If the impedance consists wholly of capacity reactance,

$$I = \frac{E}{\dfrac{1}{6.28\ n\ C}}.$$

If the impedances consist of resistance and capacity reactance in combination, then

$$I = \frac{E}{Z} = \frac{E}{\sqrt{R^2 + Y^2}}$$

$$I = \frac{E}{\sqrt{R^2 + \left(\dfrac{1}{6.28\ n\ C}\right)^2}}.$$

SECTION XIV CHAPTER V

ALTERNATING CURRENT

EFFECT OF CAPACITY IN A CIRCUIT

1. What constitutes "capacity" in an alternating circuit.

2. How is energy stored in a circuit possessing electrostatic capacity?

3. What measures the capacity of a circuit?

4. What is the effect of capacity in an alternating circuit upon the phase relations between the current and the impressed e.m.f.? Explain fully.

5. State the formula for the "capacity-reactance" of an alternating current circuit possessing a given capacity. Tabulate the meaning of each letter.

6. What is the angle between the current and the "capacity e.m.f." in an alternating circuit? Explain why this particular angle exists. Is it an angle of lead or an angle of lag? Explain fully why.

7. State Ohm's Law as applied to alternating current circuits possessing resistance and capacity. Tabulate the meaning of each letter.

8. A 10 microfarad condenser is connected in series with a 300-ohm non-inductive resistance coil across a 110-volt, 60-cycle alternator:

(*a*) How many amperes does the circuit carry?

(*b*) What is the power factor?

(*c*) Does the current lag or lead with respect to the impressed e.m.f.?

9. Required the e.m.f. necessary to set up an alternating current of 2 amperes through a condenser having a capacity of 5 microfarads, the frequency being 60 cycles per second.

SECTION XIV CHAPTER VI

ALTERNATING CURRENTS

RESISTANCE, INDUCTANCE AND CAPACITY IN SERIES AND PARALLEL

As an example of the effect of capacity in a circuit in connection with resistance consider Fig. 573. Here a non-inductive resistance coil of 100 ohms is connected in series with a condenser of 4 microfarads capacity across a 2,000-volt, 130-cycle source. Required: The impedance, the current and the angle of lead.

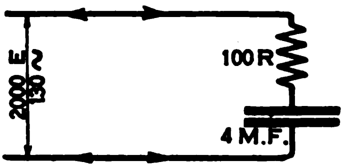


Fig. 573.—Resistance and capacity in series.

The capacity reactance of the condenser will be:

$$Y = \frac{1}{6.28\ n\ C} = \frac{1}{6.28 \times 130 \times 0.000{,}004} = 306 \text{ ohms.}$$

The combined impedance of the resistance coil and the condenser will be:

$$Z = \sqrt{R^2 + Y^2} = \sqrt{100^2 + 306^2} = 322 \text{ ohms.}$$

In Fig. 574 lay off A-B, 100 units long. At the point B construct the line B-C, now drawn downward to represent capacity reactance instead of upward as is customary in connection with magnetic reactance. This line will be 306 units long. The connecting line A-C will represent the combined impedance 322 ohms. The current which will flow through this circuit will be:

$$I = \frac{E}{Z} = \frac{2000}{322} = 6.21 \text{ amperes.} \quad \frac{R}{Z} = \cos \Phi, = \frac{100}{322} = 0.311,$$

which corresponds to an angle of lead, Φ, of 72°. Next consider the effect of introducing an inductance coil of 0.3 of a henry and with a negligible resistance, in series with this circuit, Fig. 575. The reactance of this coil will be $6.28\ n\ L = X$; $6.28 \times 130 \times 0.3 = 245$ ohms.

As the magnetic reactance is diametrically opposed to the capacity reactance this will be plotted upward from C to D.

245 units long. The net reactance in favor of capacity will then be: 306 − 245 = 61 ohms capacity reactance. The new impedance will now be:

$$Z = \sqrt{(AB)^2 + (BD)^2}; = \sqrt{100^2 + 61^2} = 117 \text{ ohms.}$$

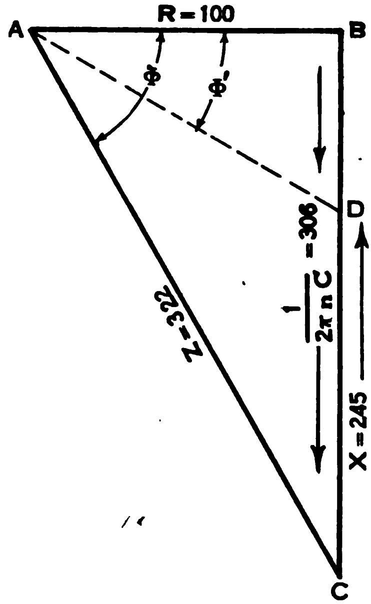


Fig. 574.—Vector diagram showing the relation between resistance, magnetic reactance, capacity reactance and total impedance in a circuit.

The new current will be:

$$I = \frac{E}{Z} = \frac{2000}{117} = 17.09 \text{ amperes.}$$

The new angle of lead, Φ', will be

$$\frac{R}{Z} = \cos \Phi', = \frac{100}{117} = 0.855,$$

corresponding to an angle of 31°.

Thus is observed the apparent paradox of an **additional impedance** connected in series, causing a **reduction** in the **total impedance** and an actual **increase** in the **current** flowing from 6.21 amperes to 17.09 amperes. If the magnetic reactance were further increased from *C-D* to *C-B*, or if

$$6.28\, n\, L = \frac{1}{6.28\, n\, C},$$

then X will exactly neutralize Y, and R will equal Z, and the angle Φ will become zero.

In the preceding example no account is taken of the energy that is lost in either the inductance coil or condenser. Now power is required to supply the core losses and copper loss in an inductance coil and to reverse the dielectric strains in a condenser. In practice, then, the conditions are not exactly as shown in Fig. 572, but more nearly as represented in Fig. 576. Here the inductive drop in a circuit is represented by *D-B*. This consists of two components, *D-E*, an energy component in phase with *A-D*, and *E-B*, a wattless component perpendicular thereto. The capacity e.m.f. likewise, instead of being in the direction *B-F*, is in the direction *B-C*, having a small component

B-H or E-G in phase with A-D to supply the losses in the condenser and a wattless component H-C. The impressed voltage required to overcome the total impedance of the circuit will then be measured by the line A-C. Now the capacity drop may be shortened from B-C to B-G, where it would exactly neutralize the inductive drop D-B, thereby bringing the impressed e.m.f. into phase with the resistance, in which case the angle of lead, Φ, will disappear. But although the power factor would then be 100% the voltage necessary to supply a given current in the circuit would be increased over the amount necessary to overcome the resistance A-D by the energy component of the reactance D-E and the energy component of the condenser E-G.

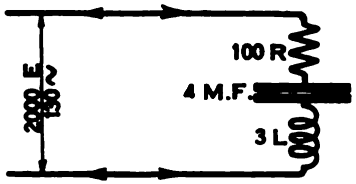


FIG. 575.—Addition of inductance to circuit shown in Fig. 573.

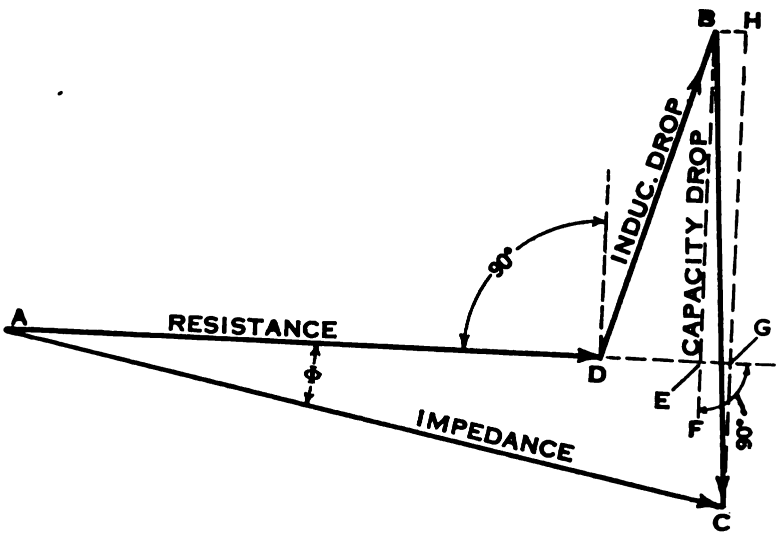


FIG. 576.—Vector diagram showing actual effect, including losses, in a circuit possessing resistance, magnetic reactance and capacity reactance.

Therefore, no matter how perfectly the capacity balances the inductance in a circuit, it is impossible to dodge the energy losses which must be supplied.

Resistance, Magnetic Reactance and Capacity Reactance in Series

A practical problem of resistance, magnetic reactance and capacity reactance in series, which will include these losses, will now be considered, Fig. 577. Assume a non-inductive resistance *A*, of 200 ohms, an inductive reactance *B*, of 19.5 ohms resistance and 0.2 henry inductance and a 15 microfarad condenser with a power factor of 8.72% all connected in series across a 2,200-volt, 60-cycle line. Required, the voltage across each device, the current and the power factor of the entire circuit. The impedance of the resistance coil will be represented by the straight line *A-B*, 200 units long, in Fig. 578 The reactance of coil *B* is 6.28 $n\,L = 6.28 \times 60 \times 0.2 = 75.36$ ohms. The impedance of this coil will be:

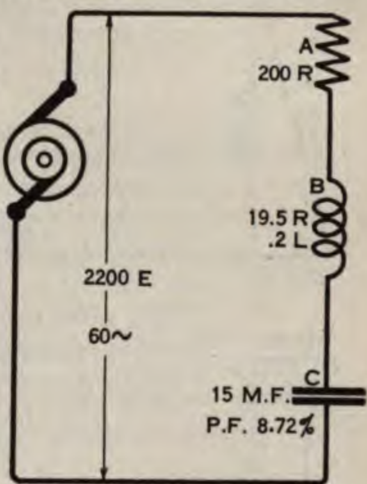


FIG. 577.—Resistance, magnetic reactance and capacity reactance in series.

$$Z_x = \sqrt{R^2 + X^2} = \sqrt{19.5^2 + 75.36^2} = 77.7 \text{ ohms.}$$

The vector for this is shown at *C-D-E*. The reactance of condenser *C* is

$$\frac{1}{6.28\, n\, C} = \frac{1}{6.28 \times 60 \times 0.000{,}015} = 177 \text{ ohms.}$$

It is not possible to express the energy component of a condenser's impedance in actual ohms as the real ohmic resistance is infinite. This effect may be expressed, however, as an energy component in equivalent ohms of the condenser's total impedance, and to do so the power factor of the condenser must be obtained. This may be accomplished by putting a voltmeter, ammeter and wattmeter in circuit with the condenser, connecting it to an A. C. source of supply and reading the instruments. The ratio of the watts to the volt-amperes gives the cosine of the angle of lead. In this example the power factor is thus supposed to have been obtained as previously stated. The im-

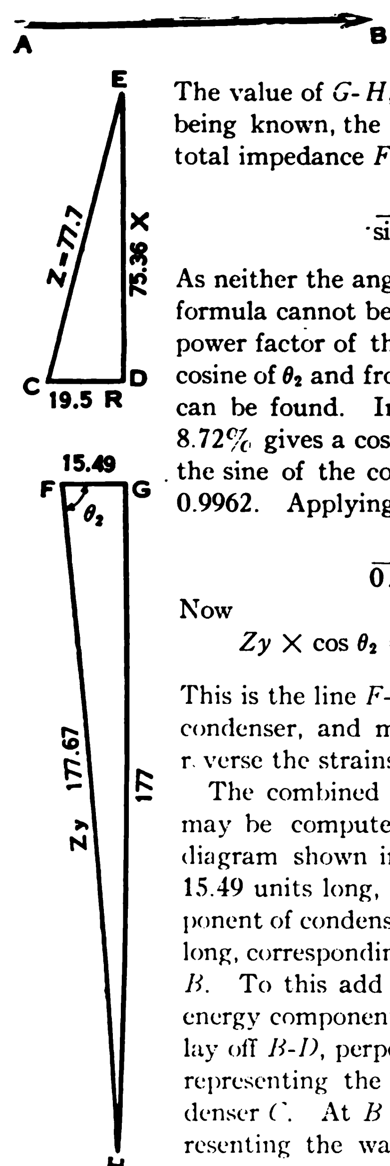


FIG. 578.—Vector diagrams for the impedances of A, B, and C in Fig. 577.

pedance triangle for the condenser is constructed at F-G-H. The value of G-H, 177 ohms, and the power factor being known, the energy component F-G and the total impedance F-H can be ascertained. Now

$$\frac{G\text{-}H}{\sin \text{ of } \theta_2} = F\text{-}H.$$

As neither the angle θ_2 nor its sine are known, this formula cannot be applied directly. However, the power factor of the condenser is a measure of the cosine of θ_2 and from a table the corresponding sine can be found. In this case, the power factor of 8.72% gives a cosine of 0.0872 and from the table the sine of the corresponding angle is found to be 0.9962. Applying the above formula,

$$\frac{177}{0.9962} = 177.67.$$

Now

$$Zy \times \cos \theta_2 = 177.67 \times 0.0872 = 15.49.$$

This is the line F-G, the energy component of the condenser, and measures the power required to reverse the strains in the dielectric.

The combined impedance of the three devices may be computed after constructing the vector diagram shown in Fig. 579. First lay off A-F, 15.49 units long, corresponding to the energy component of condenser C. To this add F-G, 19.5 units long, corresponding to the energy component of coil B. To this add G-B, 200 units long, which is the energy component of the coil A. At the point B, lay off B-D, perpendicular to A-B, 177 units long, representing the wattless component of the condenser C. At B erect B-C, 75.36 units long, representing the wattless component of the coil B. Reckoning this value B-C upward from the point D gives the point E, and B-E, is thus the net difference between the wattless component of the inductance coil, B, 75.36, and the wattless component of the condenser C, 177, or E-B, 101.64 ohms.

The combined impedance of the three devices will be:

$$Z = \sqrt{R^2 + (Y-X)^2} = \sqrt{234.99^2 + (177 - 75.36)^2} = 256.02 \text{ ohms.}$$

The current which will flow in this circuit will be:

$$I = \frac{E}{Z} = \frac{2200}{256.02} = 8.5 \text{ amperes.}$$

Since

$$\frac{R}{Z} = \frac{234.99}{256.02} = 0.9178 = \cos \Phi, \text{ and}$$

the power factor is therefore 91.78%.

"Wattless Currents"

It is common to hear the expression **"wattless power"** or **"wattless current"** in connection with alternating systems. Now

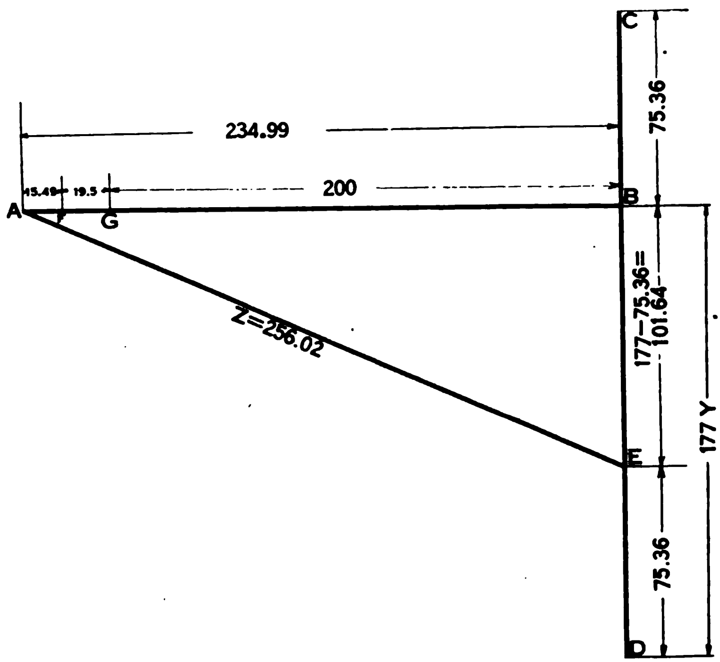


FIG. 579.—Vector digram showing the summation of impedances *A*, *B*, and *C* in Fig. 577.

there is no such thing as a wattless current! Current cannot be made to flow without the expenditure of energy and the rate at which this energy is expended is expressed in watts. There is always a component of the impressed e.m.f. in phase with the current which it produces. There is also another component which is not in phase with the current at all. The correct method of representing the actual conditions can best be understood from a consideration of Fig. 580. Consider an electrical circuit in which the voltmeter registers 1,000 volts and the ammeter 1,000 amperes. The power factor indicator shows 0.866 as the cosine of the angle of lag which corresponds to an angle of 30°. The impressed voltage, 1,000, is repre-

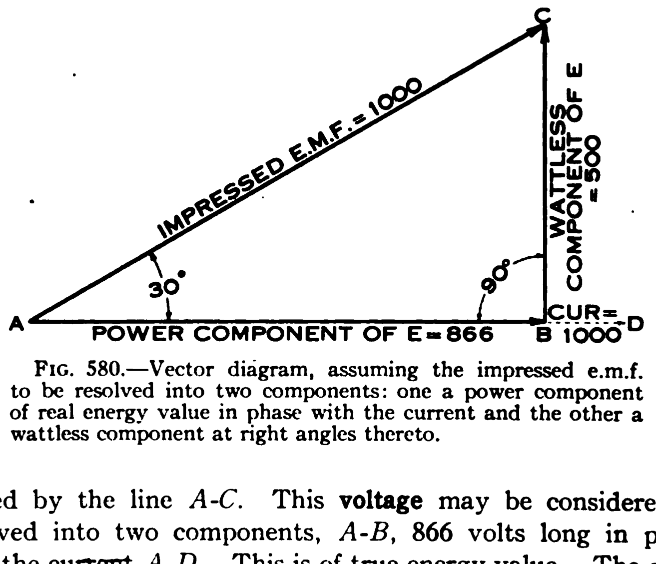


FIG. 580.—Vector diagram, assuming the impressed e.m.f. to be resolved into two components: one a power component of real energy value in phase with the current and the other a wattless component at right angles thereto.

sented by the line *A-C*. This **voltage** may be considered as resolved into two components, *A-B*, 866 volts long in phase with the current *A-D*. This is of true energy value. The other component, *B-C*, is 90° from the current and in this case would amount to 500 volts. *B-C* is called the **wattless component** of the impressed voltage. As it is 90° away from the current it represents no real energy. The **real** power in the circuit is the **effective voltage** E times the **total current** I, thus $E_f \times I =$ $866 \times 1{,}000 = 866{,}000$ watts. In Fig. 581 the current wave I is shown lagging Φ or 30° behind the e.m.f. wave, E. The conditions represented in Fig. 580 correspond to the position of the current and voltage waves at G. Here the current is at the

crest of the wave so that the ammeter shows 1,000 amperes but the voltage has fallen below the crest, due to the phase displacement and therefore reads 866 volts.

Instead of resolving the voltage into two components the conditions may be represented by Fig. 582. Here the current, *A-C*, of 1,000 amperes, is supposed to be resolved into two components, the power component, *A-B*, 866 amperes, in phase with the voltage *A-D*, 1,000 volts, and the wattless component, *B-C*, of 500 amperes, 90° away from the voltage. The actual power in the circuit is the **effective current** I, times the **total voltage** E, thus $I_f \times E = 866 \times 1{,}000 = 866{,}000$ watts. Now the points H on the waves in Fig. 581 represent the conditions from this view-

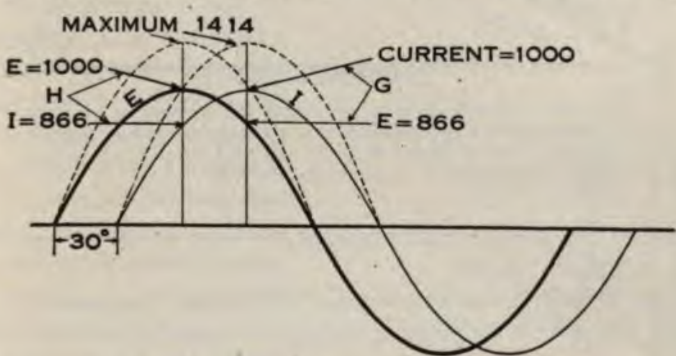


FIG. 581.—Relation between various currents and voltages in Figs. 580 and 582.

point. Here the e.m.f. has reached the crest of the wave, 1,000 volts, but the current because of its lag has not yet reached the top of the wave. The instrument readings are designed to represent the virtual voltage and current while the dotted lines indicate that both voltage and current actually reach a maximum of 1,414.

Instead of employing **power factor indicators** as formerly, the tendency in central stations today is toward the employment of the **wattless factor indicator.** This instrument is practically the same as a power factor indicator. In the above illustration, the needle of such an indicator would point 30° from the perpendicular. If the instrument were a power factor indicator, at this angle, there would be marked on the scale the cosine of 30°, or 0.866. Now, if instead of the cosine there were marked at this

same point the figure 0.5, which is the sine of 30°, the instrument would be called a wattless factor indicator because the number to which the needle points indicates the wattless component

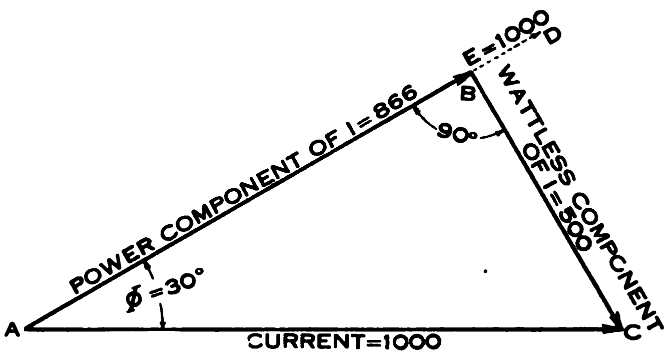


FIG. 582.—Vector diagram, assuming the current in a circuit to be resolved into two components, one a power component of real energy value in phase with the impressed e.m.f., the other a wattless component at right angles thereto.

instead of the energy component of the current with regard to the e.m.f. in the circuit

It has already been pointed out that when X equals Y in a circuit, the circuit behaves as though it possessed neither magnetic reactance nor capacity reactance, but resistance only. The energy losses n the reactance coils and the dielectric osses in the condenser must be supplied, however. Thus, in a circuit Fig. 583, possessing a resistance, A, a magnetic reactance, B, and a capacity reactance, C, the reactance, B, may be adjusted to exactly balance C. In such a case the drop across A is represented by the line A-B, Fig. 584, and the drop across B by the line B-D. This drop is resolved into two components, B-C, to supply the losses in the inductance coil, of true energy value, and the wattless component, C-D, perpendicular thereto. Next will be the drop across the condenser, C, represented by the line D-E. This drop

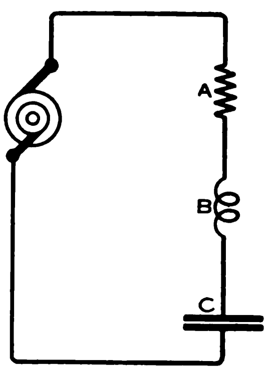


FIG. 583. Resistance, magnetic reactance and capacity in series.

in turn is resolved into two components, *D-C*, the wattless drop and *C-E*, the energy volts, which supply the dielectric losses in the condenser.

The impressed voltage from the alternator on the three devices in series will be the line, *A-E*. As this is in phase with the current which it produces, which in turn is in phase with the resistance drop, *A-B*, the power factor is 100%. That is, there is no angle between the impressed voltage and the resistance drop. But the voltage *A-B*, required to overcome the resistance of coil *A*, is increased by the component *B-C*, to supply the losses in the coil *B*, and the component *C-E*, to supply the losses in the dielectric of the condenser, *C*. So notwithstanding the fact that the line as a whole possesses unity power factor, the actual energy delivered to the circuit is increased from that required by the resistance coil *A*, to the extent of the losses in *B* and *C*. If the capacity reactance were less than the magnetic reactance, the conditions would be as represented in Fig. 585, where *A-B* represents the drop across coil *A*, *B-D* the drop across coil *B*, and *D-C* the drop across condenser *C*. The impressed voltage would then be *A-C* and the current would lag by the angle Φ. If the capacity reactance were greater than the magnetic reactance, Fig. 586 would represent the conditions. Here *A-B* is the drop across coil *A*, *B-D* the drop across coil *B*, and *D-F* the drop across condenser *C*. Obviously the impressed e.m.f. would be *A-F*, and the current would lead this voltage by the angle Φ. In this case the energy component of *B* would be *B-C* and the wattless component *C-D*,

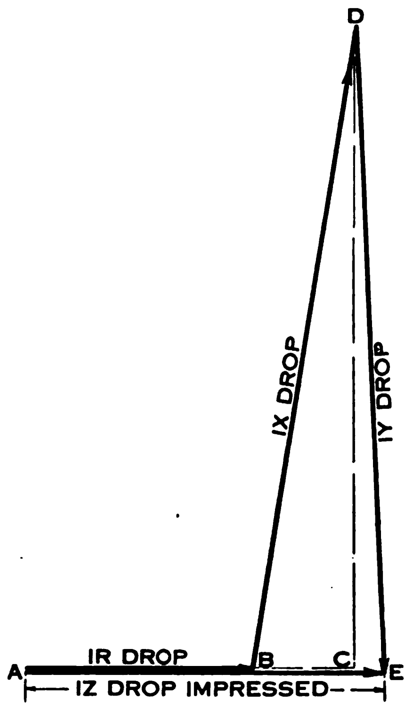


FIG. 584.—Vector diagram illustrating the relations existing between the various voltages shown in Fig. 583.

while the energy component of C would be D-E, and the wattless component, E-F.

INDUCTANCE AND CAPACITY IN PARALLEL

Inductance and capacity are seldom in series. They are usually in multiple. The capacity effect is made up of the line wires separated by the dielectric of the air, the capacity of any cable that may be included overhead or underground and the apparatus that is connected therewith, consisting of motors, transformers and generators, as shown in Fig. 587. The principal part of the inductance is found in the apparatus rather than in the line and is therefore in parallel with the capacity of the aerial lines and cables in circuit.

The inductance of alternators and transformers may amount to several henrys and the capacity of a system is by no means small, amounting in many instances to several microfarads. Underground cables often have a capacity in the vicinity of one half microfarad per mile.

As a practical example of inductance and capacity in parallel consider a condenser of two microfarads representing the capacity of a system in parallel with an inductance of 0.5 henry corresponding to the apparatus in the circuit, Fig. 588. These are connected to an alternator delivering 2,000 volts at 130 cycles. Required: The current in each device and the line current.

The energy losses in each of these devices will be neglected for the purpose of illustration. The impedance of the condenser will be:

$$\frac{1}{6.28\ n\ C} = Y.$$

$$\frac{1}{6.28 \times 130 \times 0.000{,}002} = 613 \text{ ohms.}$$

The impedance of the inductance will be:

$$6.28\ n\ L = X$$

$$6.28 \times 130 \times 0.5 = 408 \text{ ohms.}$$

To combine impedances in parallel their reciprocals representing their relative conductances must be added:

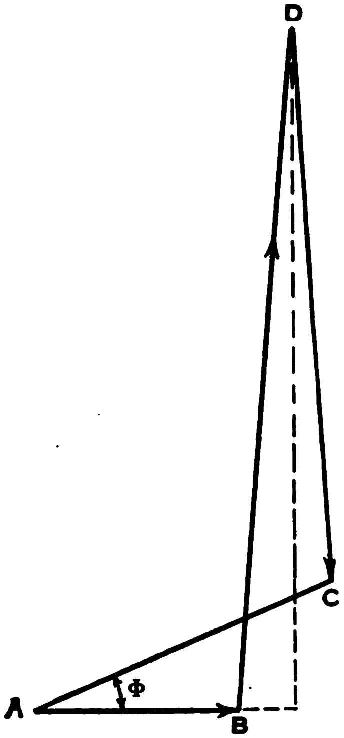


FIG. 585.—Result of lowering the capacity e.m.f. and its effect upon angle Φ.

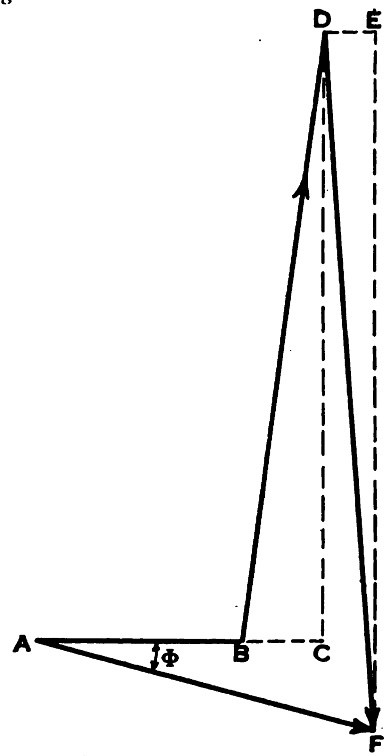


FIG. 586.—Result of increasing the capacity e.m.f. and its effect upon angle Φ.

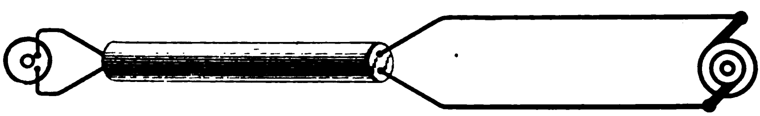


FIG. 587.—Capacity reactance and magnetic reactance in parallel.

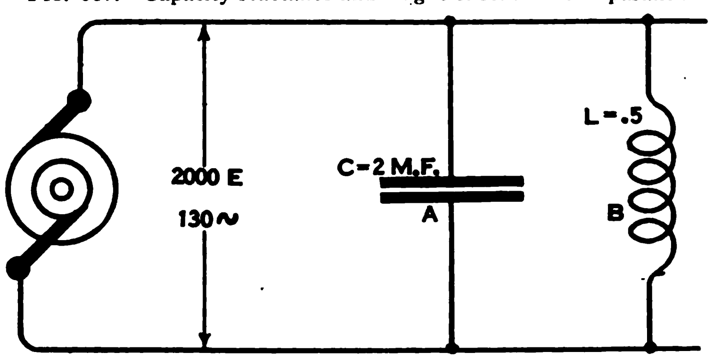


FIG. 588.—Capacity reactance and magnetic reactance in parallel.

The reciprocal of B is:

$$\frac{1}{408} = 0.00245$$

The reciprocal of A is:

$$\frac{1}{613} = 0.00163$$

$$\text{The combined reciprocals} = 0.00082$$

The geometric sum of these reciprocals will be their difference (for they are in opposition), which is, as shown, 0.00082.

The reciprocal of the geometric sum of the reciprocals is

$$\frac{1}{0.00082} = 1{,}219 \text{ ohms impedance.}$$

The current which will flow from the alternator to supply both these devices in parallel will be:

$$I = \frac{E}{Z} = \frac{2000}{1219} = 1.64 \text{ amperes.}$$

The current in B will be:

$$I = \frac{E}{X} = \frac{2000}{408} = 4.9 \text{ amperes.}$$

While the current in A will be:

$$I = \frac{E}{Y} = \frac{2000}{613} = 3.26 \text{ amperes.}$$

The current in the line supplying both devices, then, is very much less than the current in either device singly, instead of the arithmetical sum of these two, as would be the case in a

direct-current multiple circuit. This is because the currents in A and B are in diametric opposition to each other. The condenser acts as a species of generator, storing energy on one part of the cycle and delivering it to the inductance coil during another part of the cycle. As a matter of fact all the alternator has to supply is the difference between what the condenser and the inductance coil take. Thus the condenser may be regarded as a generator, furnishing 3.26 amperes in parallel with the alternator's 1.64 amperes, which combine to give the inductance coil, B, 4.9 amperes. It is evident that if A's impedance equaled B's impedance and there were no losses encountered, the line current from the alternator would be zero.

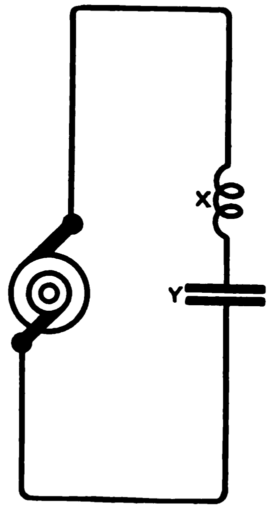


FIG. 589.—Magnetic-reactance and capacity-reactance in series.

In any multiple circuit when X equals Y the reciprocals of X and Y are equal. As they are in opposition, the geometric sum of the reciprocals is zero. The reciprocal of the geometric sum of the reciprocals will therefore be $\frac{1}{0}$ = infinity impedance.

$$\frac{E}{\text{infinity } Z} = \text{zero current in the main line.}$$

Resonance

When **X** and **Y** are in **series,** as in Fig. 589, the line **voltage** and **current increase** as the value of 6.28 n L approaches the value of $\frac{1}{6.28\ n\ C}$. When **X** and **Y** are in **multiple,** as in Fig. 588, the line **current diminishes** as the value of 6.28 n L approaches the value of $\frac{1}{6.28\ n\ C}$. In **both cases** the **power factor improves** as 6.28 n L approaches $\frac{1}{6.28\ n\ C}$.

When a circuit possesses magnetic reactance and capacity reactance the condition resulting therefrom is called **resonance.**

Resonance cannot exist with inductance alone or with capacity alone. Whenever there is inductance and capacity, there is some resonance. When $6.28\, n\, L$ equals $\frac{1}{6.28\, n\, C}$, there is perfect resonance.

Voltage Resonance

The conditions for perfect resonance, then, are that with a given frequency and current, the capacity of a circuit and the inductance of that circuit are so related that the counter e.m.fs. set up by them are equal. When the inductance and capacity are in series, there is **voltage resonance.** Under such conditions, the voltage may rise to many times the initial voltage of the alternator. An illustration may be found in the following example:

Consider an alternator in series with a condenser, as in Fig. 590. Let the alternator generate a wave of e.m.f. which sends a wave of current into the condenser as shown. At the end of the alternation the condenser is charged and the respective polarities of condenser and alternator are indicated. Now if the inductance of the alternator and the capacity of the condenser are such that $6.28\, n\, L$ for the alternator equals $\frac{1}{6.28\, n\, C}$ for the condenser, then as the alternator reverses polarity at the end of an alternation, Fig. 591, the condenser in series with the alternator sends a current back through the circuit so that at the end of this alternation the sum of the two voltages store current in the condenser under a total pressure of 4,000 volts, as in Fig. 592. Now, as the alternator reverses polarity again, as in Fig. 593, the e.m.f. of the condenser synchronizes with that of the alternator, due to the particular frequency existing, and the condenser discharges under an e.m.f. of 4,000 volts in series with the alternator's 2,000, charging the condenser on this swing to 6,000 volts, as in Fig. 594. As the alternator again reverses polarity, the 6,000-volt charge of the condenser discharges in series with the alternator, as in Fig. 595, and the voltage swings still higher. Thus, every time the condenser discharges it gets behind it a boost from the alternator and the voltage swings still higher and higher. This produces the condition known as resonance.

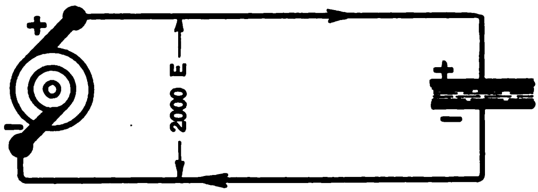


Fig. 590.

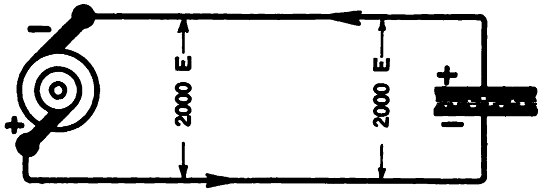


Fig. 591.

Fig. 592.

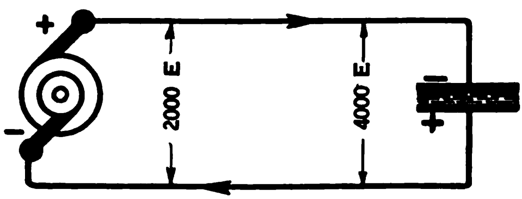


Fig. 593.

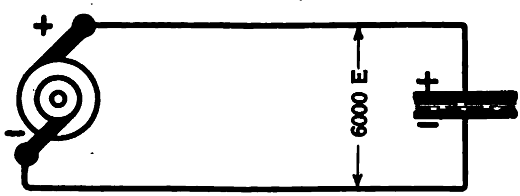


Fig. 594.

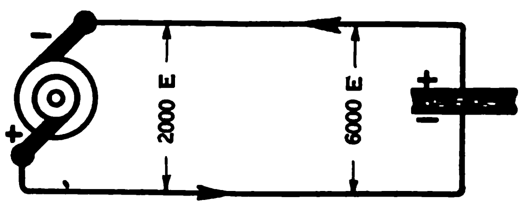


Fig. 595.

Many illustrations of resonance are found in mechanics. If a certain key is struck on a piano, a guitar or banjo nearby may be caused to emit a distinct sound, as the string whose natural period of vibration is the same as that of the piano is induced to vibrate in sympathy. A person singing a particular note may cause the globe on a chandelier to vibrate in sympathy until it is shattered. A tuning fork set in vibration and touched to a table will cause it to vibrate in sympathy. The table top forms a resonator. The induced vibrations, greater and greater in amplitude under each succeeding alternation, are an illustration of resonance.

As a practical illustration of voltage resonance, consider the circuit shown in Fig. 596. Here, a 250-volt, 60-cycle alternator is connected in series with a 2.5-ohm resistance, A, an inductance coil, B, of 0.44 henry with negligible resistance and a condenser, C, of 16 microfarads capacity also with negligible losses. The values of L and C are chosen so that the magnetic reactance, X, and the capacity reactance, Y, will balance each other and thereby illustrate perfect resonance:

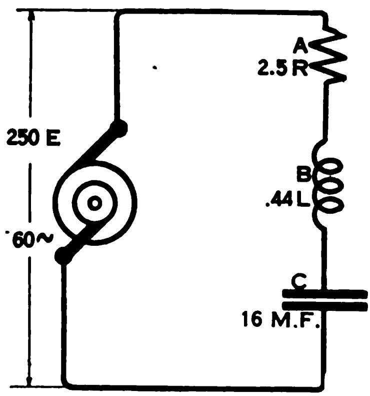


Fig. 596.—Resistance, magnetic-reactance and capacity-reactance in series

Thus $X = 6.28\, n\, L = 6.28 \times 60 \times 0.44 = 165.8$ ohms.

$$Y = \frac{1{,}000{,}000}{6.28\, n \times M.F.} = \frac{1{,}000{,}000}{6.28 \times 60 \times 16} = 165.8 \text{ ohms.}$$

As X equals Y their combined impedance will be zero. The current that will flow in this circuit will therefore be:

$$I = \frac{E}{Z} = \frac{E}{\sqrt{R^2 + (X-Y)^2}}$$

$$I = \frac{250}{\sqrt{2.5^2 + (X-Y=O)^2}} = 100 \text{ amperes.}$$

The vectors for these three impedances are shown in Fig. 597 where E-D is the resistance of A, F-E is the magnetic reactance

of B and E-F is the capacity reactance of C. As these two latter cancel each other it is evident that the whole impedance is merely the resistance E-D.

Now as 100 amperes flows through this circuit, the drop across A will be $I \times R = Er = 100 \times 2.5 = 250$ volts. The drop across B will be $I \times X = Ex = 100 \times 165.8 = 16{,}580$ volts. The drop across C will be $I \times Y = Ey = 100 \times 165.8 = 16{,}580$ volts. The vectors for the voltages are shown in Fig. 598. Here, D-E represents the drop on A, E-F represents the drop on B and F-E the drop on C. The 16,580 volts across either B or C is due to resonance. It will be observed that the drop across B and C combined is zero as these voltages are in opposition. If B alone were in circuit, the drop would be merely 250 volts, or the e.m.f. of the alternator. If C alone were in circuit there would likewise be but 250 volts drop across it. It is only when both are in circuit that this resonant rise of potential, limited only by the resistance in circuit, can take place. Practically, the resistance of the alternator and the energy lost in the inductance and capacity devices prevent the potentials rising indefinitely. Nevertheless even with partial resonance there is sometimes such a rise in potential that the insulation of the apparatus, such as the alternators, transformers and even the insulators on transmission lines are broken down.

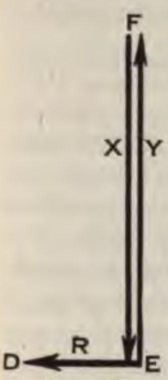


FIG. 597.

It must be noted that **resonance occurs** at a certain **particular frequency.** Should the **frequency** be **increased,** the value of **X will rise.** But at the same time that an increase in frequency increases X it **reduces** the value of **Y.** Thus, where there is resonance in a circuit, **altering** the **frequency** will **check it.**

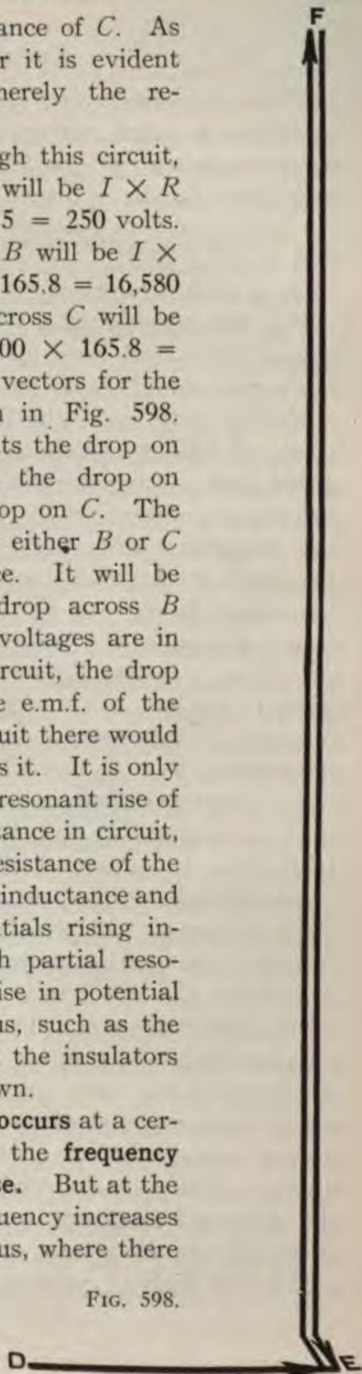


FIG. 598.

Current Resonance

When inductance and capacity are in parallel the resulting condition is called **current resonance.** There is always some resonance whenever there is any inductance and capacity in multiple. As the value of $6.28\ n\ L$ approaches the value of $\frac{1}{6.28\ n\ C}$ resonance is increased, and when the values are equal, there is perfect resonance.

Fig. 588 represented a considerable degree of current resonance. If X had been made equal to Y in that example the resonance would have been perfect. The result of **current** resonance is to make the **line current indefinitely small.** The result of **voltage** resonance is to make the **line voltage indefinitely high. Current** resonance is highly **desirable** because it relieves the alternator of the necessity of furnishing the wattless component of current to the load. With perfect current resonance there will be no wattless component of current and the power factor will be 100%. The leading current of the capacity supplies the lagging current of the inductance and the circuit as a whole behaves as though it contained neither capacity nor inductance. **Voltage resonance** is **most undesirable** because of the dangerous rise in potential which may break down the insulation of the system.

The smaller the resistance in a series circuit, the greater will be the local voltages set up across the capacity and the inductance. In practice, the capacities and inductances of systems are seldom so related as to bring about perfect voltage resonance at commercial frequencies. Though whenever a capacity and inductance are in series, the partial neutralization which takes place is liable to increase the e.m.f. to a value considerably higher than that of the impressed wave. The foregoing is based upon an assumed pure sine wave. In practice, however, the e.m.f. wave differs more or less from this form and may be considered as a resultant of several sine waves of varying amplitudes and frequencies. The normal frequency of the alternator is termed the fundamental frequency. The waves which have a higher frequency than that of the impressed e.m.f. are termed the higher or upper harmonics. Although the frequency of the impressed e.m.f. may not be sufficiently high to produce resonance, some one of the com-

ponent waves or upper harmonics may have a frequency at which resonance may result. With a given resistance in circuit, the rise in voltage due to resonance is proportional to the impressed e.m.f., and as the voltage of the upper harmonics is usually small, the rise in potential is not often great. When resonance occurs with one of the upper harmonics, the form of the current wave becomes greatly distorted because while the other component waves must force the current against both resistance and reactance, this particular wave has only to overcome the ohmic resistance and therefore sends a greater current through the circuit in proportion to its voltage than do the other e.m.f. waves.

Alternating current induction motors constitute an inductive load which always involves a bad power factor. At partial loads on these motors, the power factor is particularly bad. It has already been stated that every generator will run as a motor if supplied with the same kind of current as that which it generates as a dynamo. Thus an alternator with its separate D. C. exciter will run as a motor provided it has its field separately excited with direct current and its armature is supplied with alternating current of the same voltage and frequency as that which the machine would produce as a generator. When so operated the machine is called a synchronous motor for it possesses the property of running synchronously with the A.C. source of supply. That is, it runs at precisely the same speed as a motor, pole for pole, as the generator which supplies it. In fact, the two machines operate as though they were geared together instead of flexibly connected by wires, and the motor will operate for an indefinite time without varying a single revolution from the speed which is determined by the frequency of supply.

Now such a motor possesses this remarkable property: If the field is under-excited the current which it takes into its armature lags behind the impressed e.m.f. If the excitation is increased, the armature current will be brought into phase with the impressed e.m.f. and the motor will operate with a power factor of 100%. If the excitation of the field is still further increased, that is, if the machine is over-excited, the current which the armature absorbs will lead with respect to the impressed e.m.f. Thus the power factor of such a motor is

adjustable. With an over-excited field and the consequent leading current, it behaves like capacity in a circuit. In fact, it may be employed to act as a condenser of gigantic capacity in absorbing a leading current which may be employed to neutralize the lagging current, due to induction motors or any other inductive load connected in parallel therewith. Thus, if a 100 horse power induction motor with a power factor of 85% is connected to the line, the addition of a synchronous motor of suitable capacity and with its field adjusted so as to cause it to operate with a leading power factor of 85%, would exactly neutralize the lagging power factor of the induction motor. The transmission line supplying the two would then deliver current without either a lagging or leading component, but with a power factor of 100%.

A synchronous motor so employed is called a **synchronous** or **rotary condenser.** Sometimes such a machine is employed to run idly and deliver no mechanical power whatever from its pulley but is merely floated upon the line for the purpose of improving the power factor.

A striking illustration of the necessity for such a device is found in the Eagle Rock Sub-Station of the Southern California Power Company, where, in 1920, there was installed a synchronous condenser of 30,000 K.V.A. capacity, the largest machine of the type yet built. This machine is wound for 6,600 volts and operates at 600 r.p.m. Its rotor alone, built of sheet steel laminations to withstand the strains due to the high peripheral speed, weighs 170,000 pounds.

If a synchronous machine can be used to furnish partly mechanical power and at the same time neutralize the lagging current in a system, it is more advantageously employed than for capacity effect alone. Thus, a 100 horse power synchronous motor is utilized to the best advantage when it is loaded mechanically to the extent of 70 horse power at its pulley. At the same time it will be able to act as a rotary condenser and carry a wattless leading component of current sufficient to neutralize a lagging component from some other part of the system amounting to 70 apparent horse power.

Synchronous condensers when used solely for capacity effects are costly. Moreover, they require an attendant to supervise their operation. In 1920 there was developed a standard line

of static condensers which require no supervision and are considerably cheaper than rotary condensers. Static condenser equipments are now made for 2,300-volt service. They consist of a number of condenser units, having a capacity of 5 K.V.A. each at 60 cycles. The unit is composed of a large number of couples of metal foil with paper laminations as a dielectric, the construction being similar to that used for years in the manufacture of condensers for low voltage service. The couples are treated under vacuum to withdraw all the moisture, then immersed in oil, after which the container is hermetically sealed to prevent possible absorption of moisture from the air. The units are mounted in racks and are connected in parallel across each phase of a polyphase system through a fuse. These condensers are connected in circuit through a reactance for the purpose of damping out the higher harmonics in the voltage wave which would affect the corrective capacity of the units. They are also provided with a discharge resistance for draining the condenser charge when disconnected from the line. These condensers are now in use in capacities up to 500 K.V.A.

Calculation of Resistance, Inductance and Capacity in Parallel

The calculation of the combined impedance of multiple circuits involving resistance, magnetic reactance and capacity reactance in which the actual losses included are taken into account, will now be considered:

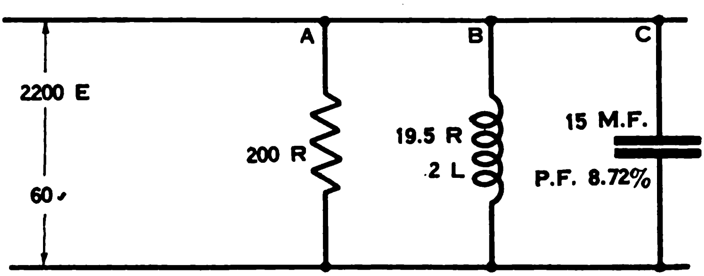


FIG. 599.—Resistance, magnetic reactance and capacity reactance in parallel.

Assume a circuit, Fig. 599, consisting of a resistance, *A*, of 200 ohms, a reactance, *B*, consisting of 19.5 ohms resistance and 0.2 henry inductance, and a capacity *C* of 15 microfarads with a power factor of 8.72%. These devices are connected in

parallel on a 2,200-volt 60-cycle alternating source. Required: The current in each branch, the total current supplied by the alternator, the impedance of each branch and the combined impedance and the power factor of the system.

The magnetic reactance of B is $X = 6.28\ n\ L = 6.28 \times 60 \times 0.2 = 75.36$ ohms.

The impedance of B is

$$Zx = \sqrt{R^2 + X^2} = \sqrt{19.5^2 + 75.36^2} = 77.7 \text{ ohms.}$$

The impedance triangle for coil B is shown in Fig. 600.

The power factor of this coil may be found from:

$$\text{Cos } \theta_1 = \frac{R}{Zx} = \frac{19.5}{77.7} = 0.2509.$$

$$\text{Sin of } \theta_1 = \frac{X}{Zx} = \frac{75.36}{77.70} = 0.9698.$$

The capacity reactance of C is:

$$Y = \frac{1{,}000{,}000}{6.28\ n\ M.F.} = \frac{1{,}000{,}000}{6.28 \times 60 \times 15} = 177 \text{ ohms.}$$

As the power factor of the condenser is 8.72%, the cosine of the angle of lead is 0.0872. From a trigonometric table the sine of this angle will be found to be 0.9962.

The capacity impedance of C will be:

$$Zy = \frac{Y}{\sin \theta_2} = \frac{177}{0.9962} = 177.67.$$

The impedance triangle for condenser C is shown in Fig. 601.

Having the impedances, A-B-C, their reciprocals must next be taken in order that they may be added. The reciprocal of A is

$$\frac{1}{R} = \frac{1}{200} = 0.005.$$

The reciprocal of B is

$$\frac{1}{Zx} = \frac{1}{77.7} = 0.0128.$$

The reciprocal of C is

$$\frac{1}{Zy} = \frac{1}{177.67} = 0.0057.$$

As pointed out in a previous example the reciprocal triangles must now be constructed for B and C. In these triangles the angles of lag or lead from the corresponding impedances must be preserved.

F FIG. 601—Vector diagram for impedance of branch *C*, Fig. 599.

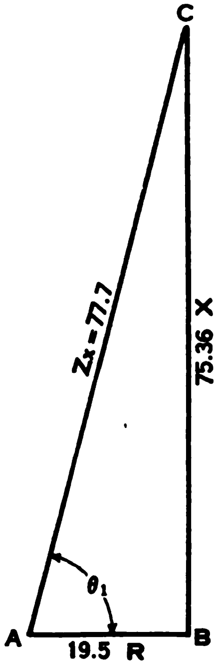


FIG. 600.—Vector diagram for impedance of branch *B*, Fig. 599.

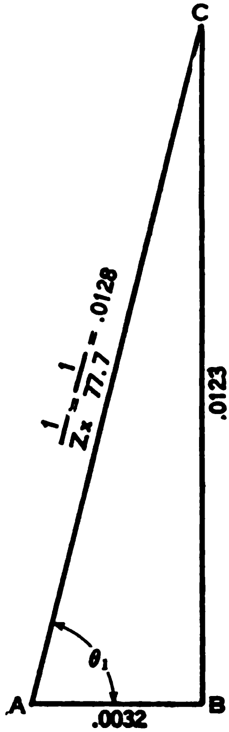
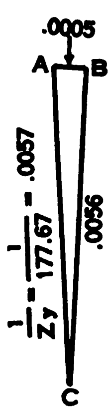


FIG. 602.—Reciprocal triangle derived from impedance triangle, shown in Fig. 600.



· FIG. 603.—Reciprocal triangle for impedance triangle shown in Fig. 601.

Referring to Fig. 600. which represents the impedance triangle for B, the reciprocal triangle, Fig. 602, may be constructed by first making:

$$\frac{1}{Zx} = A\text{-}C = \frac{1}{77.7} = 0.0128$$

and preserving the angle θ_1 from Fig. 600, between A-B and A-C

$$\frac{1}{Zx} \cos \theta_1 \text{ gives the line } A\text{-}B = 0.0128 \times 0.2509 = 0.0032.$$

This is the energy component of the reciprocal triangle for coil B.

$$\frac{1}{Zx} \sin \theta_1 \text{ gives the line } B\text{-}C = 0.0128 \times 0.9698 = 0.0123.$$

This is the wattless component in this same triangle.

The reciprocal triangle for the capacity impedance will now be constructed, Fig. 603.

$$\frac{1}{Zy} \times \cos.\ \theta_2 = 0.0057 \times 0.0872 = 0.0005.$$

This is the energy component of the reciprocal triangle for the capacity and must be plotted horizontally, A-B, Fig. 603, preserving the angle θ_2 between A-B and A-C.

From a table it is found that the sine of the angle whose cosine, $\theta_2 = 0.0872$, is 0.9962.

The wattless component may be obtained from

$$\frac{1}{Zy} \sin \theta_2 = 0.0057 \times 0.9962 = 0.0056.$$

The reciprocals of all of the energy components must now be added as in Fig. 604. Here A-B is the energy component of the reciprocal triangle for the capacity impedance, B-C, the energy component of the reciprocal triangle for the magnetic impedance, and C-D the reciprocal of the resistance. These total 0.0087. Perpendicular thereto the line D-E is erected, which is the wattless component in the reciprocal triangle for the magnetic impedance, 0.0123. In direct opposition thereto is the line D-F, which is the wattless component from the reciprocal triangle for the capacity impedance, 0.0056. Subtracting D-F from D-E gives D-G, 0.0067.

The geometric sum of the reciprocals will now be:

$$\frac{1}{Z} = \sqrt{AD^2 + DG^2} = \sqrt{0.0087^2 + 0.0067^2} = 0.01098.$$

The reciprocal of the geometric sum of the reciprocals is

$$Z = \frac{1}{0.01098} = 91 \text{ ohms.}$$

The total current will be

$$I = \frac{E}{Z} = \frac{2200}{91} = 24.4 \text{ amperes.}$$

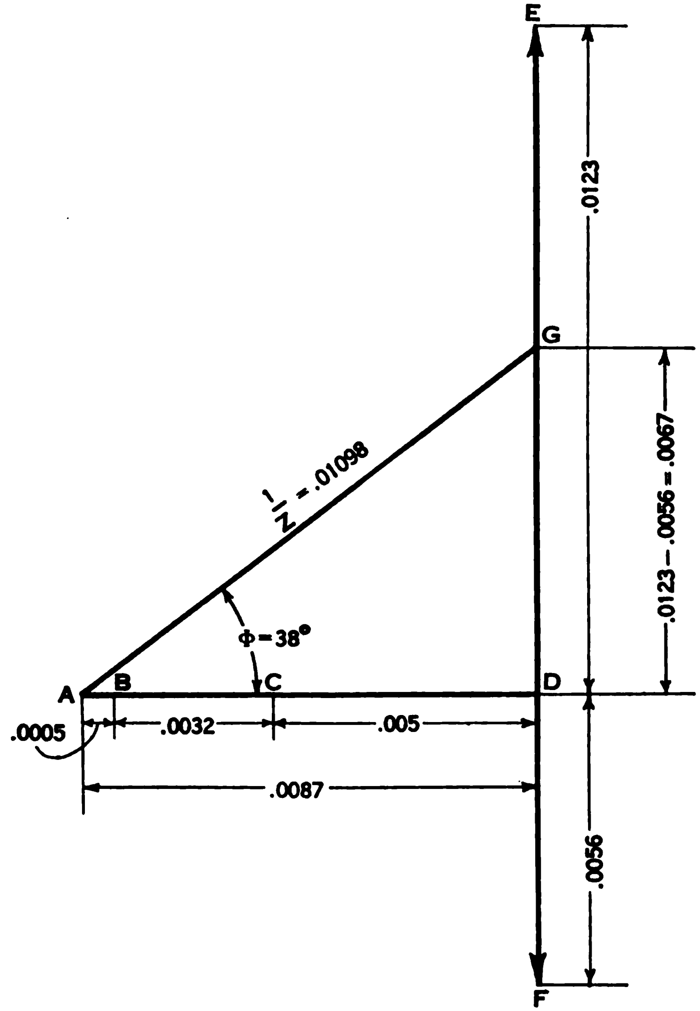


FIG. 604.—Vector diagram showing summation of reciprocals of various impedances A, B and C, Fig. 599.

The power factor for the entire load will be,

$$\text{Cos } \Phi = \frac{A\text{-}D}{A\text{-}G} = \frac{0.0087}{0.01098} = 0.7923,$$

or a power factor 79.23% lagging.

$$\text{The current in } A \text{ will be } I = \frac{E}{R} = \frac{2200}{200} = 11 \quad \text{amperes.}$$

$$\text{The current in } B = I = \frac{E}{Zx} = \frac{2200}{77.7} = 28.3 \text{ amperes.}$$

$$\text{The current in } C = I = \frac{E}{Zy} = \frac{2200}{177.67} = 12.3 \text{ amperes.}$$

The arithmetical sum of these currents is 51.6 amperes, but the geometric sum taking account of the difference in their phase angles is only 24.4 amperes.

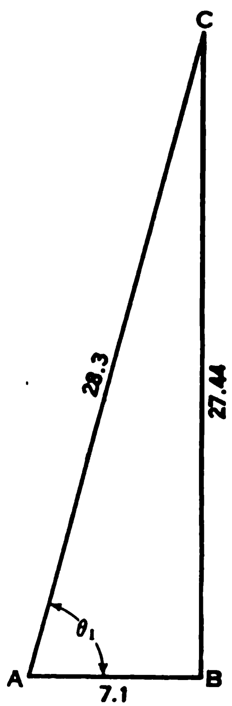


FIG. 605.—Vector diagram for current in branch B, Fig. 599.

It will be observed that in **multiple** circuits, where there is a **difference in phase** angle **between** the **currents** in the various branches, that the **geometric sum** or **total current** will always be **less** than the **arithmetical sum** of the currents in the separate branches.

While the reciprocal triangles for the various impedances in a multiple circuit are a measure of the separate currents, the actual vectors, showing the currents and to which the reciprocal triangles are proportional, may be readily constructed. Thus in Fig. 605, $I \times \cos \theta_1 = 28.3 \times 0.2509 =$ 7.1 amperes. This is laid off as A-B, representing the energy component of the current in branch B. $I \times \sin \theta_1 = 28.3 \times 0.9698 = 27.44$ amperes. This is laid off as B-C, 27.44 units long, erected perpendicular to A-B, which represents the wattless component of the current in the magnetic reactance. A-C represents the total current 28.3 amperes in this circuit with an angle θ_1 between the total current and the energy component.

The current vector for branch C may be similarly constructed, Fig. 606. Thus $Iy \times \cos \theta_2 = 12.3 \times 0.0872 = 1.07$ amperes. This is laid off as A-B, and represents the energy component of the condenser's current. Perpendicularly downward from B the wattless component is laid off. This is $Iy \times \sin \theta_2 = 12.3 \times 0.9962 = 12.25$ amperes. A-C is thus the total current in the condenser, 12.3 amperes, leading the energy component A-B by the angle θ_2.

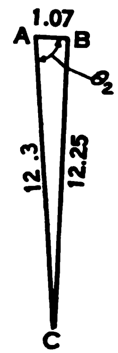


FIG. 606.—Vector diagram for current in branch C, Fig. 599.

Fig. 607 represents the summation of the various currents to show the total line current. Thus A-B represents the energy component of the current in the capacity reactance, 1.07 amperes; B-C, the energy component of the current in the magnetic reactance, 7.1 amperes; C-D, the current in the resistance, 11 amperes. These total 19.17 amperes. Perpendicular thereto at the point D is erected the line D-E, 27.44 amperes long, representing the wattless component of the current in the magnetic reactance. Perpendicularly downward from D is the line D-F, representing the wattless component of the current in the capacity reactance, 12.25 amperes. As these are in opposition their geometric sum is their arithmetical difference or the line D-G, which is 15.19 amperes. The total current from the alternator is therefore:

$$I = \sqrt{AD^2 + DG^2} = \sqrt{19.17^2 + 15.19^2} = 24.4 \text{ amperes.}$$

A general rule may now be laid down for the purpose of combining two or more impedances of any character whatsoever, in multiple.

First: Find the reciprocal of each impedance.

Second: Multiply the reciprocal of each impedance by the cosine of its corresponding angle of displacement, which will give the horizontal component of the reciprocal of each impedance.

Third: Multipy the reciprocal of each impedance by the sine of its corresponding angle of displacement, which will give the vertical component of the reciprocal of each impedance.

Fourth: Square the sum of all the horizontal components.

Fifth: Square the algebraic sum of all the vertical components.

Sixth: Take the square root of the sum of these two squares which value will be the reciprocal of the total impedance, fron which the total impedance may be found by taking the reciproca of the final value.

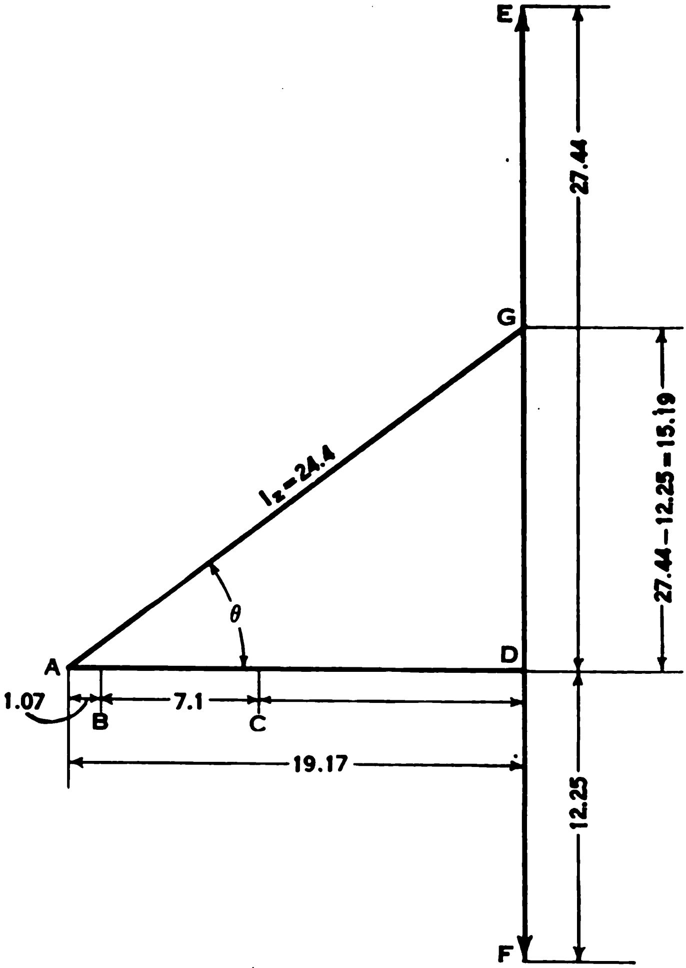


FIG. 607.—Vector diagram showing summation of currents in branches *A*, *B*, and *C*, Fig. 599.

In case one or more of the impedances are due to capacity the sum of the vertical components of the reciprocals of the capacity impedances must be subtracted from the sum of the vertical components of the inductive impedances, that is, their algebraic sum must be taken as stated, then proceed as in the

fourth, fifth and sixth steps as previously explained, in order to find the total impedance.

A simple method of solving impedances in parallel is illustrated in Fig. 608. This is a graphic solution which can be made very quickly by the aid of a drawing board, T square, triangle, protractor, and drawing compass. The same problem previously considered will now be solved by this method. The

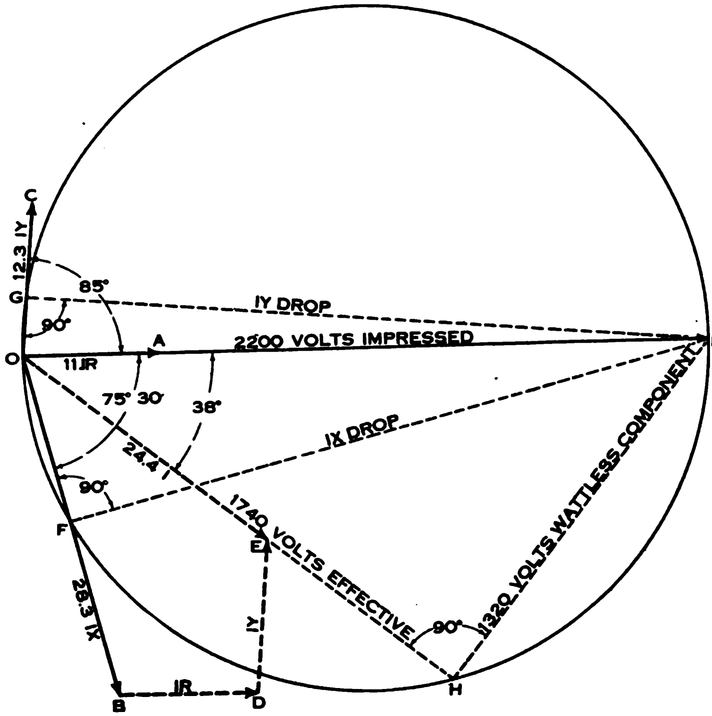


FIG. 608.—Graphic method of combining currents in any number of separate impedances in parallel.

first step is to describe a circle of such a size that the diameter *O-M* represents the voltage impressed upon the circuit to any convenient scale. As the problem under consideration involves 2,200 volts, the line *O-M* may be made 11 inches long, which will give a scale of 200 volts per inch. In view of the total current to be handled, a scale of 5 amperes per inch will be convenient. The actual scale may be arbitrarily decided in any case and will depend upon the magnitude of the currents and voltages dealt with.

In the branch A, Fig. 599, the current will be in phase with the resistance because it is a non-inductive circuit. This current will be represented by the line O-A, Fig. 608, along the line O-M, 2.2 inches long. The magnetic reactance of circuit B gives $X = 6.28 \; n \; L = 6.28 \times 60 \times 0.2 = 75.36$. The power factor of this branch may be expressed as $\frac{R}{Z_x} = \frac{19.5}{77.7} = 0.2509$ $= \cos \theta_1$, Fig. 600. From a table this cosine is found to correspond to 75°. Usually the angle of lead or lag as the case may be, is all that is wanted so that $\frac{BC}{AB} = \frac{X}{R} = \tan \theta_1$, gives the angle with less work; that is, the angle may be found from a knowledge of the reactance and resistance without the necessity of finding the impedence. Now with the aid of a protractor construct an angle of 75° from O-M and draw the line O-B, of indefinite length, which represents the direction of the current in this branch. It is a well known fact that where the line O-F cuts the circumference a right angle will be established with a line F-M and this is true for a line drawn in any direction from the point O to the circumference of the circle with respect to another line, drawn from the point of intersection to the point M. Now the line O-F will represent the ohmic drop due to resistance, and F-M will represent the inductive drop. Measuring the length of the line O-F to scale gives 2.75 inches which multiplied by 200 volts per inch equals 550 volts ohmic drop. Now the effective volts E_f divided by the resistance R, equals the current, $\frac{E_f}{R} = I$, therefore $\frac{550}{19.5} = 28.3$ amperes in this branch. This gives the length of the line O-B, which, to the scale of 5 amperes per inch = 5.66 inches long.

The capacity reactance of C is

$$Y = \frac{1{,}000{,}000}{6.28 \times n \times M.F.} = \frac{1{,}000{,}000}{6.28 \times 60 \times 15} = 177 \text{ ohms.}$$

The power factor of the condenser is given, 8.72%. From a table the angle corresponding to cosine, 0.0872, is found to be 85° from O-M, but on the opposite side of O-M from which O-B was constructed. O-B represents a lagging current and O-C a leading current. At the point where the line O-C, of indefinite

length, cuts the circle at G, draw a line, G-M. O-G now represents the energy drop in the condenser and G-M the wattless component of the impressed e.m.f. on circuit C.

To obtain the current in circuit C: Draw G-M and measure it. G-M = 10.955 inches. With a scale of 200 volts per inch, a capacity drop, Ey, of 2,191 volts, is obtained. This is due to the current through the circuit which includes the capacity reactance Y.

The current in this circuit may be found by dividing the wattless component of the capacity e.m.f. Ey, by the capacity reactance Y.

$$I = \frac{Ey}{Y} = \frac{2191}{177} = 12.3 \text{ amperes in } C.$$

To the scale of 5 amperes per inch, draw O-C, 2.46 inches long, representing a current of 12.3 amperes.

The phase angles of current in branches A, B and C now being known, their vector sum may be found. This is done by first taking the current in any branch, such as O-B, and then plotting B-D equal in length and parallel to O-A; then erect D-E equal in length and parallel to O-C. The line O-E, which now completes the figure, represents the vector sum of the currents in the three branches. O-E is 4.85 inches long and to scale of 5 amperes per inch represents 24.4 amperes. This current lags 38° behind the impressed e.m.f. O-M, as can readily be ascertained by the protractor, or, project O-E to the point H where it intersects the circle and connect H with M. It will be evident that O-H represents the effective component of the impressed e.m.f. O-M, and is in phase with the total current, O-E. According to the scale this is 8.7 inches long, which at 200 volts per inch represents 1,740 volts, while H-M, to the same scale, represents the wattless component, 6.6 inches long or 1,320 volts. The power factor of the load as a whole will evidently be:

$$\frac{\text{Effective e.m.f.}}{\text{Impressed e.m.f.}} = \frac{O\text{-}H}{O\text{-}M} = \frac{1{,}740}{2{,}200} = 0.7923 = \cos \Phi,$$

which corresponds to the indicated angle of 38° and represents a power factor of 79.23%.

It will be observed that this graphic solution permits the summation of the currents in any number of branches **without** the **calculation of** the **impedances** in these branches at all. If,

instead of three branches, there were six, the last three vectors would be added consecutively to the point E and the final line connecting the last of the vectors to the point O would represent the total current. The method is sufficiently accurate for most engineering problems and is much shorter than the mathematical solution.

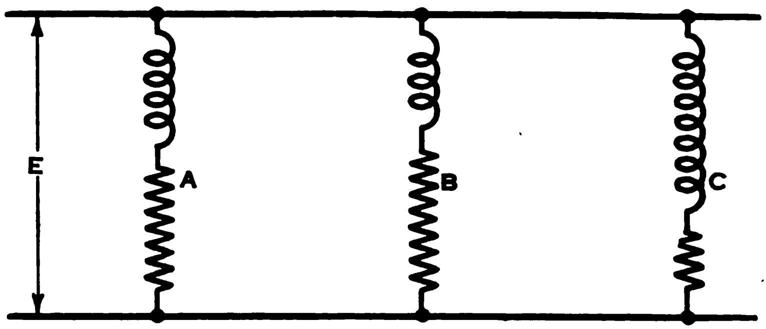


FIG. 608-A.

The combined impedance of several impedances in parallel such as A, B, C, Fig. 608-A may be easily found by dividing the line voltage by the vector sum of the currents in the various branches.

Thus:

$$\frac{E}{I_t} = Z_t$$

Where

E = line voltage.
I_t = line current.
Z_t = total combined impedance.

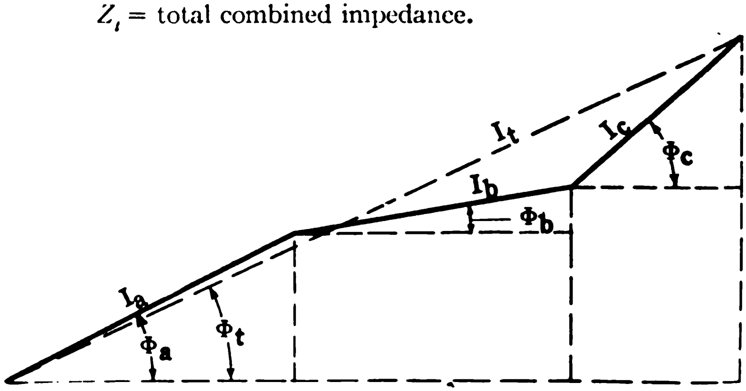


FIG. 608-B.

The line current may be obtained by the use of a vector Fig. 608-B, or may be found mathematically as follows:

$$I_t = \sqrt{(\cos \Phi_a I_a + \cos \Phi_b I_b + \ldots .)^2 + (\sin \Phi_a I_a + \sin \Phi_b I_b + \ldots .)^2}$$

Where

I_a = current in branch A.
I_b = current in branch B, etc., etc.
Φ = phase angle between current and voltage in the various branches.

It must be remembered that the sum of the various sine values must be the algebraic sum in all cases, as currents may sometimes lag and sometimes lead.

SECTION XIV CHAPTER VI

ALTERNATING CURRENTS

INDUCTANCE AND CAPACITY IN SERIES AND IN PARALLEL

1. Five amperes flow from a 60-cycle alternator through a 200-ohm resistance and a 15-microfarad condenser connected in series. Required:
(*a*) The e.m.f. across the resistance.
(*b*) The e.m.f. across the condenser.
(*c*) The e.m.f. across the alternator.
(*d*) The power factor.

2. An alternator furnishes a condenser with 15 amperes under a pressure of 2,200 volts. Assuming the angle of lead to be 90 degrees what will a wattmeter in circuit register? Why?

3. What is the combined effect of inductance, capacity and resistance in an alternating circuit upon the phase relation between the current and the impressed e.m.f.?

4. State Ohm's Law as applied to an alternating current circuit possessing resistance, inductance and capacity. Tabulate the meaning of each letter.

5. What is the impedance of a series-circuit containing 4 ohms resistance, 6 ohms "magnetic reactance" and 3 ohms "capacity reactance?"

6. An alternator is connected to a circuit having a resistance of 100 ohms, a self-induction 0.25 henry, and capacity 20 microfarads. The current flowing is 5 amperes, and the frequency 60 cycles per second.
(*a*) Find the e.m.f. or drop across the resistance, drop across the condenser and drop across the inductance.
(*b*) Determine whether the current lags behind the impressed e.m.f. or is ahead of it.
(*c*) Find the value of the impressed e.m.f. necessary to maintain a current of 5 amperes.

7. (*a*) Define the wattless component of the voltage in a circuit.
(*b*) Define the energy component of the voltage in a circuit.

8. (*a*) Define the wattless component of the current in a circuit.
(*b*) Define the energy component of the current in a circuit.

9. Distinguish between the "power factor" indicator and the "wattless factor" indicator.

10. A circuit possesses resistance and inductance in series. If capacity is added in series what will be the effect: (*a*) Upon the current? (*b*) Upon the power factor?

11. If the capacity reactance in a series-circuit equals the magnetic reactance (the resistance in circuit being negligible), what is the combined impedance; what is the line current and the effect on the voltage of the circuit?

12. A circuit possesses a resistance and an inductance in multiple. What will be the effect if capacity is added in multiple: (*a*) Upon the line current? (*b*) Upon the power factor?

13. If the capacity reactance in a multiple-circuit is equal to the magnetic reactance (the resistance in circuit being negligible) what is the combined impedance, what is the line current, and what is the effect upon the voltage?

14. When does "voltage resonance" occur in an alternating circuit? When is there partial "voltage resonance" and when would the resonance be perfect? In a given circuit how could "voltage resonance" be avoided?

15. When does "current resonance" occur in an alternating circuit? When is there partial "current resonance" and when would the resonance be perfect? In a given circuit how could "current resonance" be produced?

16. A coil having 5 ohms resistance and 7.5 ohms magnetic reactance, and a condenser having a capacity reactance of 20 ohms and a power factor of 0.06, are placed in parallel on a 220 volt circuit:
(*a*) What is the combined impedance?
(*b*) What is the current in each device?
(*c*) What is the total current?
(*d*) What is the total power factor?

17. A coil having a resistance of 5 ohms and a magnetic reactance of 8.66 ohms, and a coil having a resistance of 20 ohms and a magnetic reactance of 15 ohms, and a condenser having a capacity reactance of 80 ohms and a power factor of 0.09, are placed in multiple on a 440-volt alternating circuit. What is the total current supplied by the alternator?

18. A non-inductive resistance of 50 ohms, a magnetic reactance having 20 ohms resistance and 0.02 henry inductance, and a condenser of 35 microfarads capacity, having a power factor of 0.08, are connected in multiple upon a 220-volt, 25-cycle circuit.
(*a*) What is the total current supplied by the alternator?
(*b*) What is the total power factor?
(*c*) What is the power factor of each branch?

19. A 250-ohm non-inductive resistance, a magnetic reactance coil with resistance of 40 ohms and an inductance of 0.04 henry, and a condenser having a capacity of 12 microfarads, with a power factor of 0.075, are connected in parallel upon a 2,200-volt 60-cycle alternator.
(*a*) What is the total current?
(*b*) Does it lag or lead with respect to the impressed e.m.f.?
(*c*) What is the power factor?

ALTERNATING CURRENT

CONSTRUCTION OF ALTERNATORS

With reference to the number of alternating currents differing in their phase relation produced in an alternator, machines may be classified as either monophase or polyphase.

A monophase alternator is a machine which generates one simple alternating current. This current may bear any phase relation to the voltage of the machine, depending on the power factor of the system.

A polyphase alternator is one which generates two or more

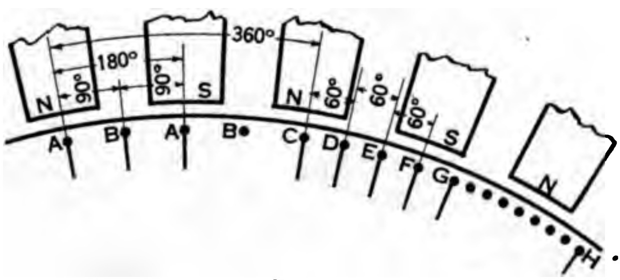


FIG. 609.

alternating currents differing in their phase relation to each other by some fixed angle. Practically, such machines are limited to two types, two-phase and three-phase. Two-phase machines generate two alternating currents differing in their phase relation by 90°. Thus, in Fig. 609, if conductors *A-A* are connected in series throughout the machine so as to form one circuit it is evident that when the voltage is a maximum in *A-A* it will be zero in *B-B*. If the first and second sets were insulated throughout and led to two separate external circuits it will be evident that the voltage in conductors *B* would differ from the voltage in conductors *A* by a fixed phase angle of 90°.

Nearly all modern alternators are constructed polyphase whether designed for polyphase or single-phase operation. Machines have a **greater output** when operated **polyphase than** when delivering **single phase**; that is, a greater kilowatt capacity from

a given amount of copper and steel is possible from a polyphase connection than from a single phase connection.

Alternators may carry on their armatures **concentrated windings** which contain but one slot or bunch of conductors per pole

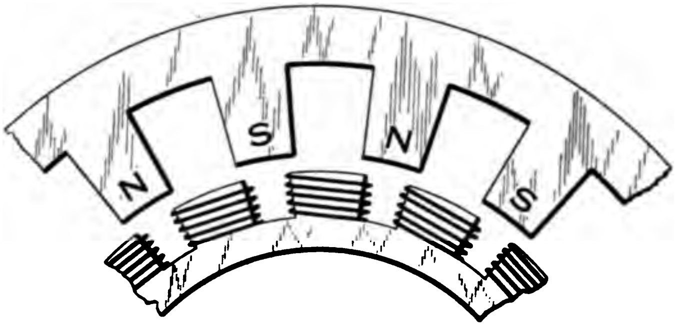


FIG. 610.—Concentrated armature winding.

as shown in Fig. 610, or they may carry **distributed windings** where the conductors are uniformly distributed in slots over the surface of the armature as in Fig. 611. Concentrated windings deliver a maximum voltage for a given number of conductors because the voltage in practically all of the conductors rises

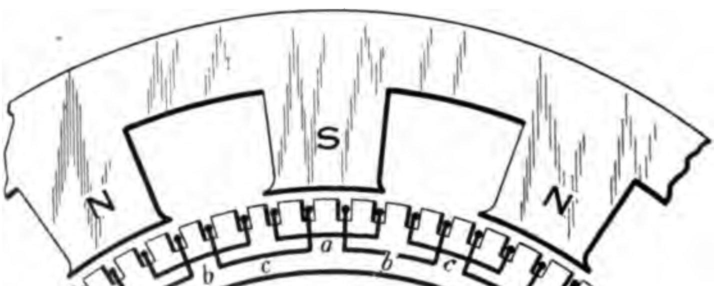


FIG. 611.—Distributed armature winding.

and falls at the same time, that is, there is no phase angle between the voltages in the different conductors. If, on the other hand, the conductors are distributed as from G to H in Fig. 609, it is evident that at a given instant the voltage will be different in every one of these conductors due to their different positions in the field. Let the voltage due to a concentrated winding of 1,000 conductors be called 1,000 volts. As the e.m.f. of all

these conductors is in phase, the vector in Fig. 612 will be a straight line 1,000 units long representing 1,000 volts.

If, instead of having the conductors so arranged as in Fig.

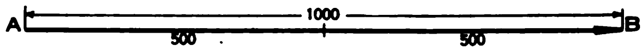


FIG. 612.—Voltage generated in concentrated armature winding.

610, the same 1,000 conductors are distributed over the armature, half of them occupying the positions *A-A*, in Fig. 609, and the other half *B-B*, 90° therefrom, then the resulting voltage will be shown in Fig. 613, where *D-C* represents the voltage from the *A-A* series and *D-E* the voltage from the *B-B* series, bearing the phase relation of 90° to each other. The delivered voltage from the same 1,000 conductors will now evidently be *D-F*, or 707 volts instead of 1,000.

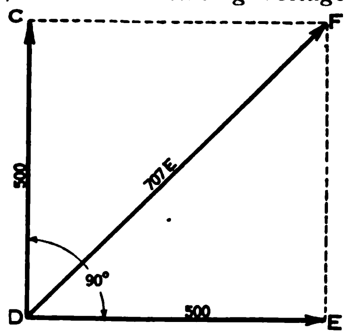


FIG. 613.—Delivered voltage at no load with partially distributed armature winding.

If, now, the same 1,000 conductors are distributed in three groups, occupying the positions *C*, *D*, *E* and *F*, in Fig. 609, having a phase relation of 60° to each other, each group will generate 333 volts instead of 500, but the three groups in series 60° apart will produce the voltage shown in Fig. 614. Here the geometric sum is 667 volts.

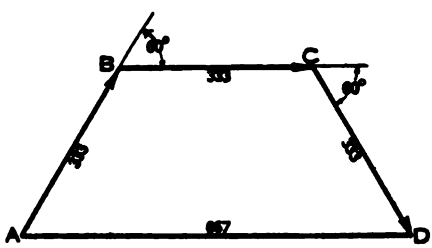


FIG. 614.—Delivered voltage at no load with greater distribution of armature winding.

If, now, the 1,000 conductors were uniformly distributed in slots around the armature circumference as between *G* and *H* in Fig. 609, it is evident that the total voltage available would be

the **average** height of a sine wave of voltage, which has been shown before to be 0.636 of the maximum or 636 volts.

Thus from the maximum voltage obtainable from a concentrated winding, where 1,000 conductors in series will give 1,000 volts, as the winding is more and more distributed the total voltage falls until with the greatest distribution possible a minimum of 636 volts is available from the same 1,000 conductors.

It might be inferred from the foregoing that the concentrated winding would be the most desirable. This, however, is not the case because the effects of armature reaction and the losses through self-induction are very great in a concentrated winding and are less in a distributed winding, hence distributed windings are usually employed. When an alternator takes its load, the voltage falls. With a uniformly distributed winding, the maximum of 636 volts might fall to between 600 and 550 volts. Should the same machine have been provided with a concentrated winding with its initial no-load voltage of 1,000, it would be found that under full load conditions the delivered e.m.f. would be lower than that of the distributed winding above referred to.

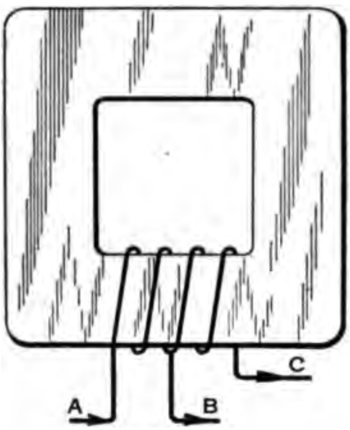


FIG. 615.—Highly inductive circuit.

One of the advantages of a distributed winding on an alternator armature as compared with a concentrated winding is the diminished self-induction encountered. It has already been pointed out that the self-induction will vary theoretically as the square of the number of convolutions in the coil. This may be explained as follows. If, in a coil wound on an iron core, Fig. 615, the current enters at A, passes through two turns and leaves at B, a certain flux will be established. When this current is interrupted the flux will cut these two convolutions and induce a certain e.m.f. If the current enters at A and is taken out at the point C it passes through four convolutions. There will therefore be produced, theoretically, twice the flux. When this current is interrupted this doubled flux collapsing on

double the number of convolutions will induce four times the e.m.f. Hence the statement that the e.m.f. of self-induction varies as the square of the number of convolutions in a coil. Now if four conductors were grouped at the point *A*, Fig. 609, in a concentrated winding, and a certain self-induction resulted, then if these conductors were subdivided and two were placed at *A* and two at *B*, making a distributed winding, the self-induction would theoretically be quartered. Practically the flux about the conductors does not vary directly with the current therein or with the turns, due to the fact that this flux is established through iron already occupied to a greater or less extent by the flux from the field coils. Nevertheless a reduction

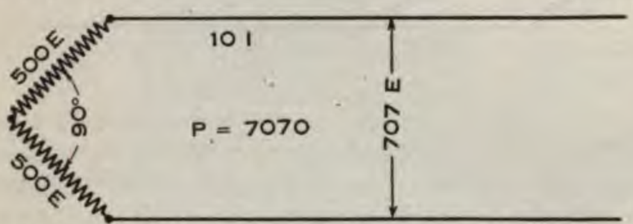


FIG. 616.—Addition of two e.m.fs., 90° apart in phase.

in the number of convolutions in a coil as effected in changing from a concentrated to a distributed winding, produces a reduction in self-induction somewhat in excess of direct proportion.

Employing a strong field reduces self-induction in the armature winding in two ways.

First: It pre-empts the armature teeth for field magnetism so that when the current in the armature conductors varies, it finds about it a poor field for its inductive operations.

Second: The greater the field flux the fewer the number of armature conductors required to generate a given voltage and consequently the less the self-induction in the armature.

As all modern alternators possess distributed windings the voltage available from a machine having 1,000 conductors distributed in two groups as shown at *A* and *B* in FIG. 609, connected single phase, as shown in Fig. 616, would evidently be 707 volts. If a load current of 10 amperes flows at unity power factor, the power delivered would be 7,070 watts. If this machine were connected up two phase as shown in Fig. 617, each phase would deliver 500 volts and 10 amperes, or 5,000

watts. Thus the two phases would deliver a total of 10,000 watts, because the fact that these two circuits were independent would not interfere with each delivering its maximum voltage. In Fig. 616 the resultant voltage is obtained at a disadvantage. In Fig. 617 the full advantage of each separate phase voltage is

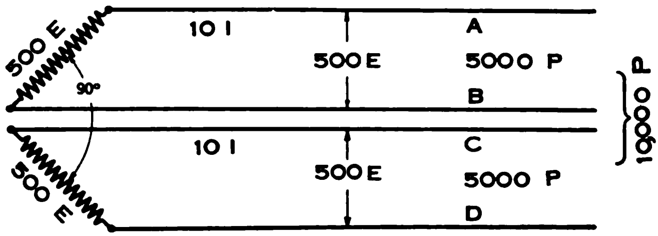


FIG. 617.—Advantage of maintaining two e.m.fs. differing in phase, in separate circuits.

obtainable. Thus a machine has a greater output as a two phaser than as a single-phase alternator.

Theoretically, for the same heating effect it may be stated in general that the single-phase output of any polyphase machine is 70.7% of its polyphase rating.

Excitation of Alternators

With reference to the methods of excitation, alternators may be either self-exciting in part or in whole, or separately excited.

A direct-current machine may have two insulated slip rings placed over a portion of its commutator. If the machine is bipolar, and one of these rings is connected to any commutator segment, and the other ring to the segment diametrically opposite, alternating current may be collected from the brushes placed on these rings, instead of the direct current obtained from the brushes on the commutator. The direct-current brushes may still be employed to excite the field and either alternating or direct current, or both, may be delivered from the same winding. When delivering alternating current the machine becomes a self-exciting alternator. This type of machine is seldom used, however, for the reason that when the alternating current reacts upon the field flux it lowers the voltage at the direct-current brushes which furnishes the exciting current and produces the flux for the alternator. There is thus a magnified reduction in the delivered voltage. It is therefore much more

satisfactory to have alternators separately excited, and all machines except a few very small ones are so excited.

Many of the earlier alternators had their exciters directly mounted upon the shafts of the alternators. An illustration of this is found in the vertical type of the turbine machines used by the Ontario Power Company on the Canadian side of Niagara Falls. Each machine carries on the top if its shaft a small

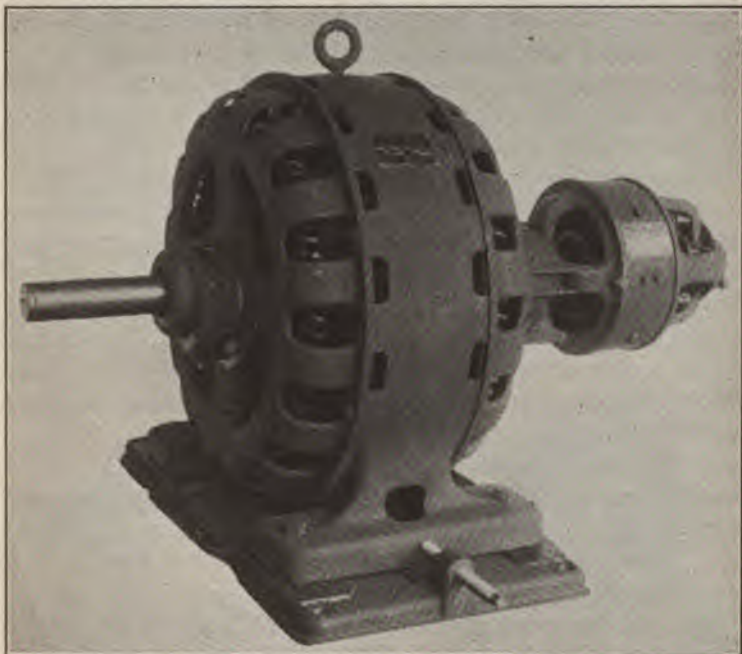


FIG. 617-A—Westinghouse belt-driven alternator with direct-connected exciter.

commutating exciter for that particular machine. Some early engine-driven alternators had their own exciters often driven by a belt from the alternator itself or from a spare pulley on the engine.

A medium-speed engine-driven alternator manufactured by the Westinghouse Electric and Manufacturing Co., with separate exciter direct connected on the same shaft, is shown in Fig. 617-A.

The direct-connected exciter is excessively large for its kilowatt capacity because of the low speed at which it must be

operated due to direct connection. The belted exciter is unsatisfactory because it is dependent for its operation upon the same prime mover as the alternator. Modern practice tends toward a more efficient arrangement.

In Power House No 1, of the Niagara Falls Power Co., on the American side, there are five vertical shaft direct-current exciters each driven by a separate water turbine and arranged to supply two sets of bus bars from either of which sets exciting current may be taken for the fields of eleven 5,000-kilowatt alternators. This makes a very satisfactory arrangement.

A third plan is in operation in the Mississippi River Power Plant at Keokuk. This employs a separate motor-generator set consisting of an induction motor direct connected to a small direct-current exciter placed close to each alternator. The induction motors for all of these sets are supplied with alternating current from a separate alternator driven by a separate water turbine. This insures exciting current at all times for the alternators regardless of the conditions of load on the alternators. Should the motor-generator exciters be operated directly from the main alternators, a sudden drop in potential due to heavy load might cause the exciter sets to slow down to such an extent that the alternators would lose their excitation.

Of the three schemes available the plan of having a group of direct current machines each operated by a separate prime mover, as in Power House No. 1 of the American Niagara Falls Power Co., is probably the most satisfactory from the standpoint of reliable service.

With reference to revolving members, alternators may be classified as follows:

First: Those with a stationary field and a revolving armature.

Second: Those with a stationary armature and a stationary field with a revolving mass of iron called a rotor.

Third: Those with a stationary armature and revolving field.

The first construction is the oldest. The early alternators all had a stationary field structure like the direct-current generator, with the armature mounted within, the current being collected by brushes placed on slip rings. The coils on the armature were all connected in series as shown in Fig. 618. As the two ends of the winding terminate on separate slip rings it is an open coil winding. Such an armature may be arranged to give 10 amperes at 2,200 volts. These windings were generally

arranged so that they could be split in half and the two halves connected in multiple as in Fig. 619. When so connected it constituted a closed coil winding. The delivered voltage from the slip rings would now be 1,100 volts and the current 20

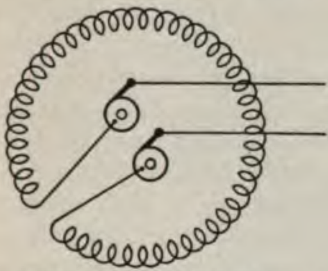


FIG. 618.—Straight series connection of alternator armature winding.

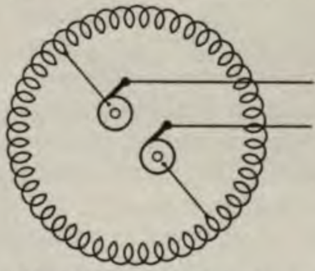


FIG. 619.—Multiple-series arrangement of alternator armature winding.

amperes. Some small alternators are still built with a revolving armature. In special cases the same winding may be supplied with a commutator from which current can be taken to excite the fields, making the machine self contained. The objection

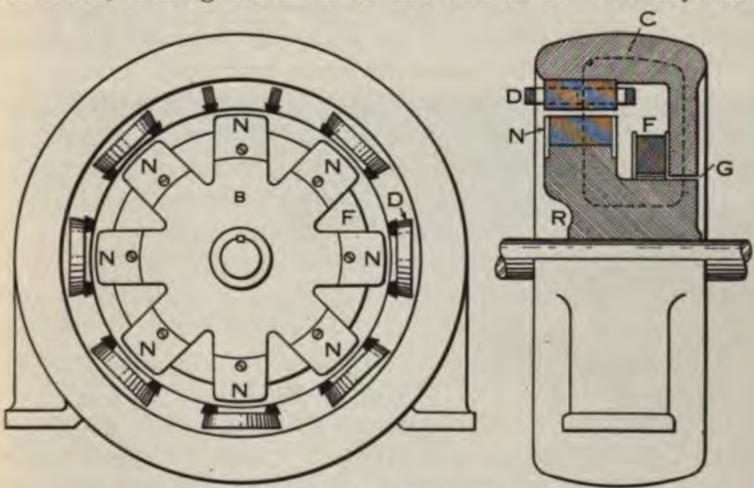


FIG. 620.—Inductor type of alternator.

to a revolving armature is that the brushes must be occasionally adjusted, and as they carry a high voltage they are dangerous to life and it would not be practical to insulate the brushes. Furthermore, it is always more difficult to insulate a winding

which revolves than one which is stationary. Hence the third arrangement is preferable.

The second type of construction embraces what is called the inductor type of alternator. An early machine of this sort is shown in Fig. 620. Here a field coil, *F*, which is stationary, excites a rotor, *R*, an end view of which is shown at *B*. Direct current magnetizes the rotor from the stationary winding and a flux is projected radially outward from the inductor blocks, *N*. This flux is caused to sweep across the armature poles which project radially inward from the frame, *C*. On these poles are the armature coils, *D*. As the flux rises and falls, an alternating e.m.f. is generated in these coils. The flux completes its circuit through the field coil by jumping a small air gap, *G*. As there is no moving wire on this machine it is easy to insulate all of the windings. The chief difficulty experienced with the inductor type of alternator is its poor regulation. This class of machine has now been generally abandoned.

Fig. 621 represents the stationary armature of a large Westinghouse alternator of the third type of construction and Fig. 621-A the revolving field structure which goes within. The armature winding, which is stationary, can readily be insulated for as high as 13,200 volts. The current is taken from fixed terminals as the generating circuit is stationary. The revolving field structure consists of a spider with a large number of magnetizing field coils alternately north and south, placed on the circumference. These coils are energized from a 220-volt source through brushes and slip rings. If the brushes require adjustment only the low voltage direct exciting current need be handled. This is the most widely used method of construction today.

Some idea of the refinement to which the design of alternating-current generators and turbines has been carried may be gained from a study of Fig. 622. For an extension to Station No. 3 the Niagara Falls Company placed orders for three generators with three different manufacturers. These machines are nearly alike in external appearance. The one here illustrated is that designed and constructed by the Westinghouse Electric and Manufacturing Company. It has a capacity of 32,500 k.v.a., or nearly 40,000 h.p. They generate 12,000 volts and deliver 1,565 amperes in each phase at 150 r.p.m. The machine weighs 325 tons and is driven by a Francis type reaction turbine, built

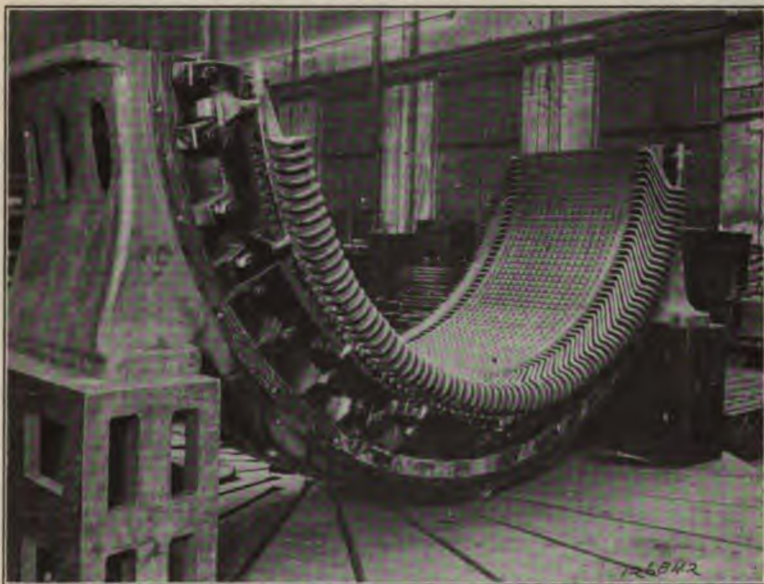


FIG. 621.—Section of stationary armature showing arrangement of winding for Westinghouse 3-phase, 60-cycle, 6,600-volt alternator of 14,285 k.v.a. capacity.

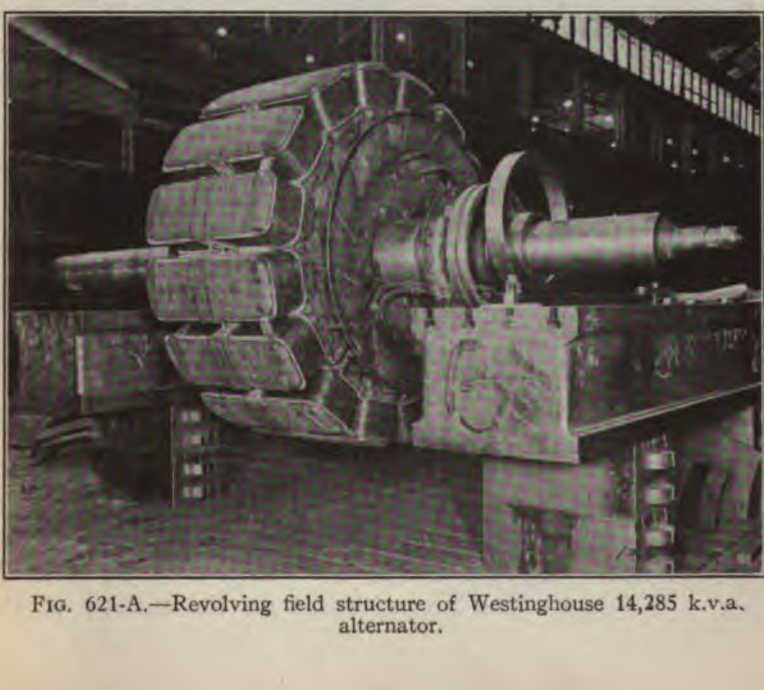


FIG. 621-A.—Revolving field structure of Westinghouse 14,285 k.v.a. alternator.

by the I. P. Morris Company. The armature has four circuits in parallel and is Y-connected. The internal revolving field is 16 feet in diameter and carries an exciting current at no load,

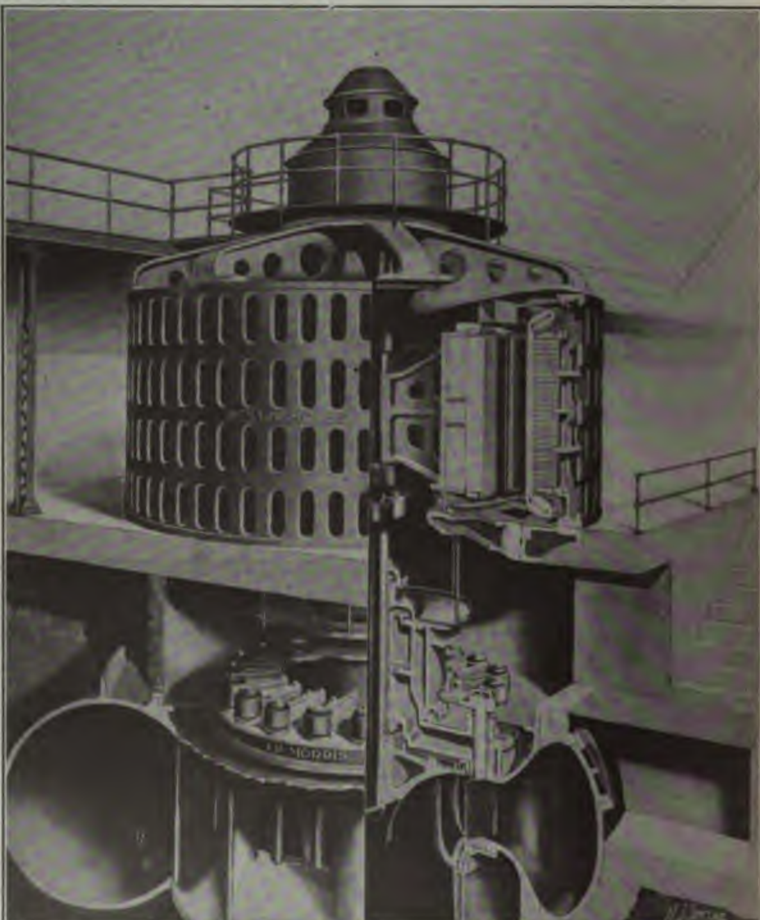


FIG. 622.—Latest type Westinghouse three-phase alternator and I. P. Morris turbine for Niagara Falls Power Company. Capacity, 32,500 k.v.a., 12,000 volts, 25 cycles, 150 r.p.m.

of 323 amperes. With full load, and 80% power factor, the excitation must be increased to nearly double this amount, or 632 amperes. The rotor and its shaft weigh 159 tons. The air gap is 0.5 inch. The normal speed at the surface of the

revolving field is 7,700 feet per minute, and the machines are guaranteed to stand 100% overspeed, or 15,400 feet per minute. The performance of this machine and the other two designed by the General Electric Company and the Allis-Chalmers Company have been equally satisfactory.

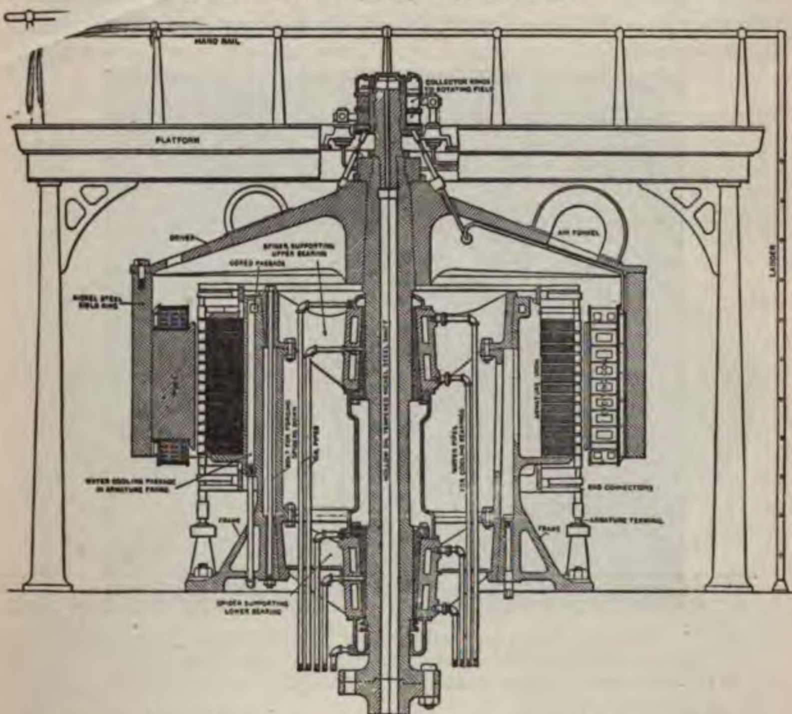


FIG. 623.—Vertical shaft, umbrella type revolving field alternator. One of the first designed by the Westinghouse Company for the Niagara Falls Power Company.

Occasionally the revolving field structure is external to the armature as in the case of the "umbrella type" revolving field alternator in Power House No. 1 of the Niagara Falls Power Co. Fig. 623 illustrates a machine of this type. This arrangement, however, is rarely used. Fig. 623-A shows a general view of an installation of machines of this type.

Fig. 623-B illustrates a typical stator for a slow speed, vertical shaft A. C. generator. Fig. 623-C shows the rotor for this same machine with the 48 poles assembled on the spider. The complete machine as installed is shown in Fig. 623-D.

Fig. 623-E shows the complete assembly of a large horizontal shaft A. C. generator. This machine is of the forced ventilation type and is quite compact considering its comparatively low voltage.

To obtain the standard frequency of 60 cycles from slow-speed engines it is required that all alternators shall have multi-

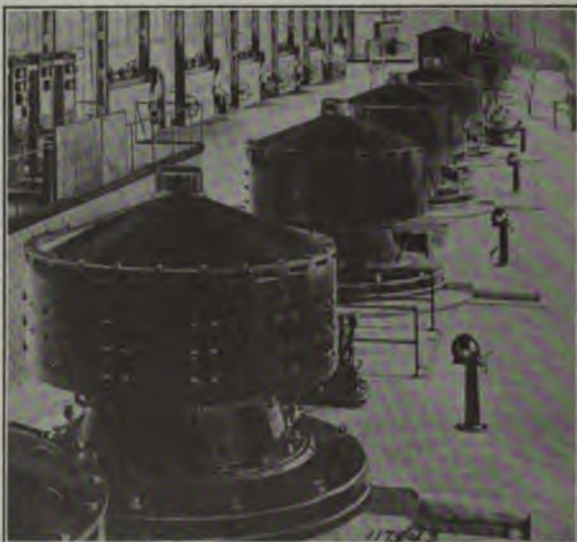


FIG. 623-A.—A general view of Westinghouse umbrella type revolving field alternators in Power House No. 1 of the American Niagara Falls Power Company.

FIG. 623-B.—Stator ring for General Electric vertical shaft alternator 300 k.v.a. capacity.

polar fields. As one cycle is produced for each revolution in a bipolar field it is evidently necessary to drive a bipolar machine 60 revolutions per second or 3,600 revolutions per minute to produce 60 cycles. The same frequency could be obtained with a 4-pole machine at 1,800 r.p.m., an 8-pole machine at 900 r.p.m. and a 16-pole machine at 450 r.p.m. Some small capacity steam-

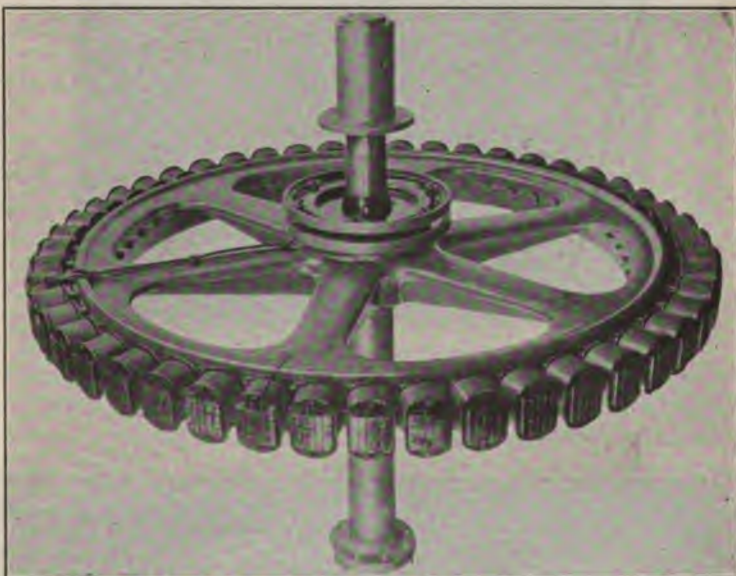


FIG. 623-C.—Revolving field structure for General Electric 300 k.v.a. vertical shaft alternator.

turbine-driven alternators are constructed with two poles. The larger machines so driven have 4 or 6 poles. Alternators driven by water turbines have from 10 to 20 poles while those operated by slow-speed Corliss engines will have upwards of 60 poles.

When an alternator takes its load the terminal voltage falls from three causes:

First: The ohmic drop in the armature winding. This is due to the resistance of the armature circuit. The fewer the number of conductors, the larger the cross-section of the conductors and the shorter the length of the total circuit, the less will be the armature resistance.

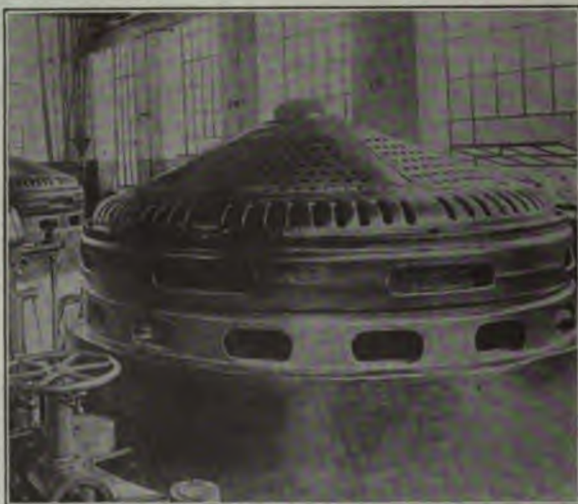


FIG. 623-D.—Complete G. E. vertical shaft alternator of 300 k.v.a. capacity in Riverdale Cotton Mill at Riverview, Alabama.

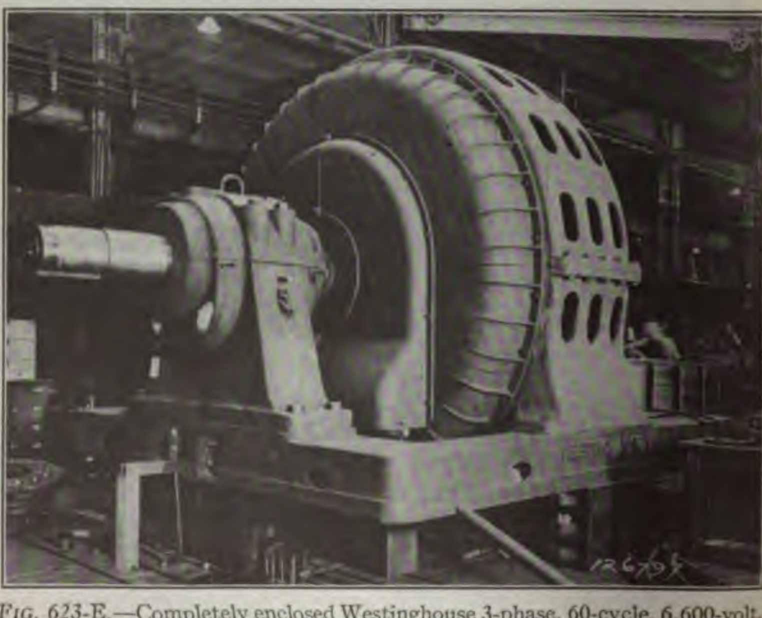


FIG. 623-E.—Completely enclosed Westinghouse 3-phase, 60-cycle, 6,600-volt, 450 r.p.m., 14,285 k.v.a. alternator.

Second: The self-induction in the armature winding. There are two e.m.fs. produced in the armature of an alternator.

The first is the generated e.m.f., due to the rotation of the armature. The second is an induced e.m.f., not due to the rotational effect or field flux at all, but brought about by the variation in flux accompanying the change of current in the armature winding. In a direct-current armature the value of the current in an armature coil is practically fixed all the time it is passing from a brush of one polarity to the next brush of opposite polarity. But in an alternator armature the current is never fixed in any conductor but is constantly changing. This involves an e.m.f. of self-induction lagging 90° behind the current whose variations produce it. Thus if in Fig. 624, *A-C* represents the rotational generated e.m.f., then the induced e.m.f. will be in the direction *C-B*, more or less opposed to the generated.

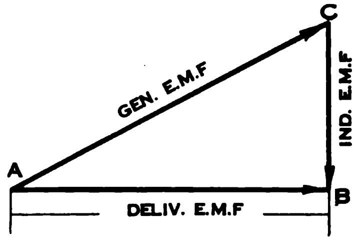


FIG. 624.

The delivered e.m.f. available for the load will then be *A-B*, which is the net difference between the inductive and that generated by rotation. Obviously the inductance of an armature should be made as small as possible for this inductance interferes just as much with the current in the circuit as the inductance encountered externally in the system. This will also emphasize the importance of using comparatively few armature conductors and a distributed winding with a minimum number of convolutions per coil.

Third: The reaction of the armature current on the field magnetism. If the current is in phase with the e.m.f., then as the armature pole *N*, Fig. 625, approaches the field pole *N'*, it is of the same sign and hence repels—and weakens—the field flux at the tip *C*. When the pole *N* gets on dead center or on the line *A-B*, assuming 100% power factor, the current and e.m.f. reverse and the armature pole becomes south and as it passes away from the field pole *N'* it attracts and builds up the flux on the pole tip *D*, Fig. 626. Assuming the weakening effect in Fig. 625 to be exactly balanced by the strengthening effect in Fig. 626, the field flux is distorted but the average value is not

materially changed. Thus if a sine wave of e.m.f. was produced as in *A*, in Fig. 627, without load, it might be assumed that the wave could be distorted somewhat into the shape shown at *B*. The lower voltage during the early part of this wave is due

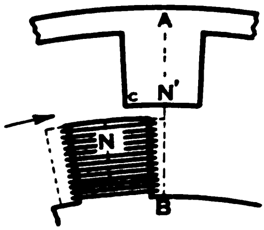


Fig. 625.

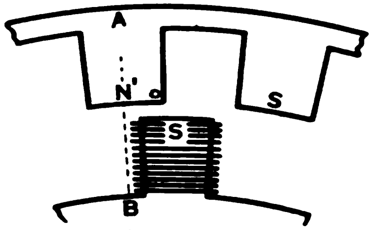


Fig. 626.

to the weakened flux at the pole tip *C* while the sudden rise to the end of the alternation is due to the increased flux at the tip *D*. While the r.m.s. (root-mean-square) value of the two waves may be practically the same and the voltmeter therefore read nearly the same in both cases, nevertheless the maximum height of the wave may be increased 30 or 40% with a resultant strain on the insulation of the system.

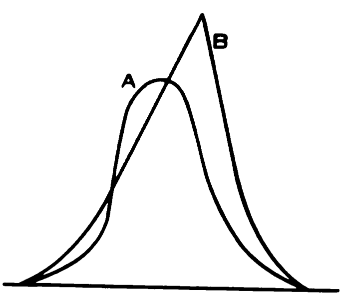


Fig. 627.

If the current **lags** in phase behind the e.m.f. due to an inductive load, then, while the **e.m.f. changes** when the armature pole is squarely on the line *A*-*B*, Fig. 625, the **current, lagging, does not change** at this instant but later. Hence the armature's polarity remains north, Fig. 628, the greater part of the time that the armature pole is passing from the position *A* to the position *B*. The result is that the armature reaction weakens the field pole but has no opportunity to produce a corresponding strengthening effect, for the polarity changes too late. Hence the total **flux** across the armature is **reduced** and with it the generated voltage.

In the latest generators of the American Niagara Falls Power Company the result of this reaction is such that it is necessary to raise the exciting current in the field coils from 323 amperes to 632 amperes to maintain the terminal voltage.

If the current **leads** with respect to the generated e.m.f. as when capacity or its equivalent is encountered, then while the e.m.f. changes when the armature pole reaches the line *A-B*, the **current leading,** reverses the polarity of the armature **in advance** of this point, so that the armature pole becomes south in the position *A*, Fig. 629, and remains such until it reaches the point *B*. Thus while it is passing across the field pole it **supplements** the magneto-motive-force of the field winding and actually **raises the field flux.**

The effects of armature reaction may then be summed up as follows: If the current and e.m.f. are in phase, the field flux is

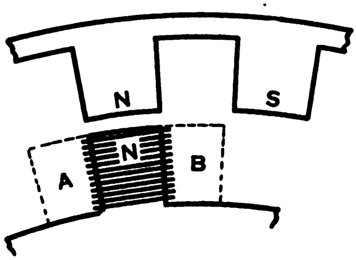


Fig. 628.

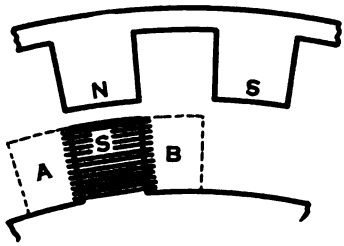


FIG. 629.

distorted but not greatly altered in magnitude. If the current lags, the field flux is battered down and the generated voltage is reduced. If the current leads, the field flux is boosted and the generated voltage increased.

It has already been stated that single-phase alternators with distributed windings have less capacity than with concentrated windings because a part of the voltage is obtained at a disadvantage due to the phase angle between the various sections of the winding.. If these sections could be made to deliver their voltages independently, a closer approximation to the arithmetical sum of their separate voltages could be more nearly realized. Thus, if in Fig. 609, instead of having conductors *C-D-E*, with their e.m.fs. 60° apart merged into one resultant voltage, they were connected up in separate circuits as shown in Fig. 630, a great gain would be effected. Thus let the conductor *E* be in series with the conductor *F* 180° away from it while the conductor *G*, 60° away from *E*, is in series with *H*, which is likewise 60° away from *F*. The conductor *I*, in phase with *K*, is also 60° away from *G*. If the terminals of these three sets of conductors were brought to six separate wires, three alternating

currents could be obtained in separate circuits which would bear the phase relation to each other shown in Fig. 631. For purposes of economy it is desirable to merge these circuits into

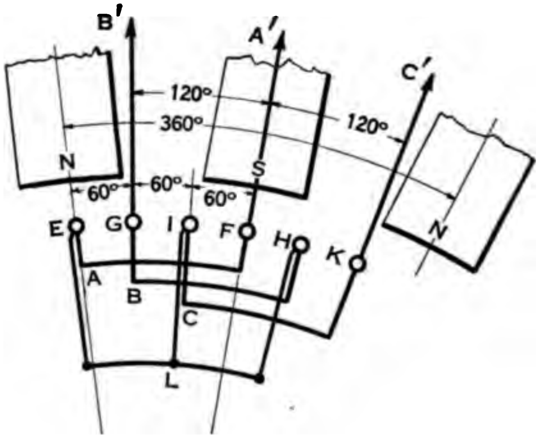


FIG. 630.—Three-phase armature winding connected in Y.

one consisting of a smaller number of wires. A symmetrical arrangement which would be economical as to copper could not be obtained if these currents were 60° apart in phase. In order that the entire surface of the armature may be economically occupied. the windings should be placed 60° apart as shown.

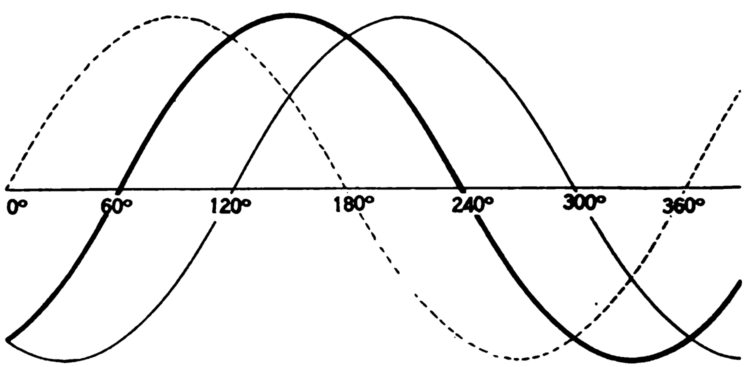


FIG. 631.—Three e.m.fs., generated 60° apart in phase.

These may be connected, however, so as to produce e.m.fs. 120° apart by connecting the circuits as in Fig. 630. Here the terminals of E, I and H, 120° apart in their time phase, are brought to a common connection at L. The remaining terminals, G, F, and K, likewise 120° apart, lead to the external circuits,

A', B' and C'. Such an arrangement is pictured in Fig. 632 and the phase relation of the resulting e.m.fs. in Fig. 633. Notwithstanding the fact that the voltages in these separate circuits were generated 60° apart in phase, as shown at A, B and C, Fig. 634, a reversal of the phase, O-B, so as to throw it in the direction O-D, results in the three windings delivering e.m.fs. in the direction O-A, O-C and O-D, 120° apart in phase. This is made possible by tying the first ends of the phases A and C, Fig. 630, and the last end of phase B to the common point L. This is in effect a reversal of phase B consisting of conductors G and H, and produces the result shown in Fig. 634.

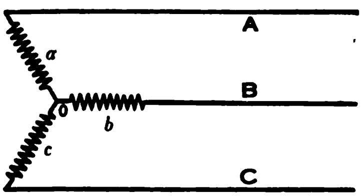


FIG. 632.—Y connection of alternator.

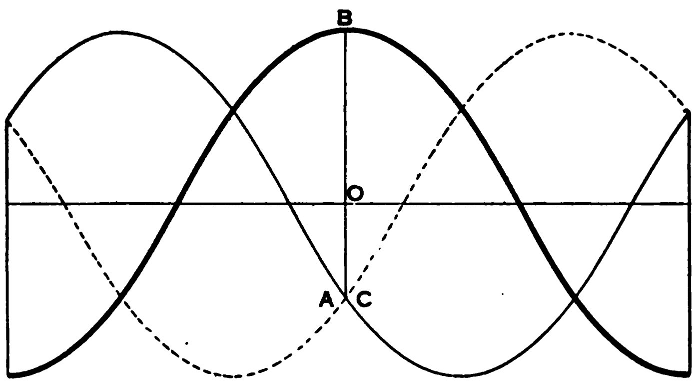


FIG. 633.—Three e.m.fs., 120° apart in phase.

In Fig. 633, it will be seen that there is practically an equal flow of current in both directions at the same time; thus if the outgoing current in wire B, Fig. 632, is a maximum as at O-B, in Fig. 633, then the sum of the currents in the wire A or O-A and the current in the wire C, or O-C, in a negative direction will exactly equal the current in the wire B. The current thus starts out in A, Fig. 632, and returns through B-C. As it dies down in A it starts out in B and returns through C and A. The currents reach their maximum in a given direction in A, B and C, 120° of the cycle apart in time phase.

When the windings of an alternator are connected as shown in Fig. 632, they are said to be connected in **"Y"** or **"Star."**

If instead of connecting the three separate phases in this way as in Fig. 630, they are connected in a closed circuit as in Fig. 635, the same winding will give a larger current at a lower voltage in the external circuit. This is said to be connected in Δ (delta) or **mesh.** To make this connection, the two ends of adjacent phases 60° apart are joined together and to the external circuit.

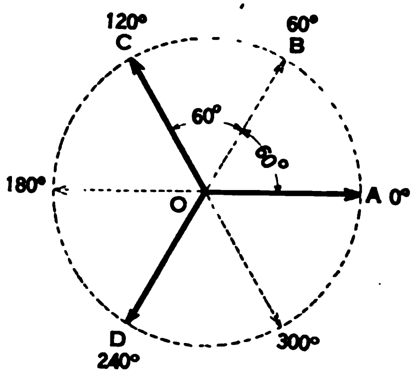


FIG. 634.—Reversal of one phase to alter the 60° relation between the different phases to 120°.

The winding shown in Fig. 630 connected in Y, is shown in Fig. 636 rearranged to produce a Δ connection. Here the wires E and G are joined together and a lead from this common connection is taken to the line wire B'. The leads I and F are likewise joined together and a lead from this common connection is taken to the line wire A'. The wires H and K are joined together and a lead from this common connection is taken to the line wire C'.

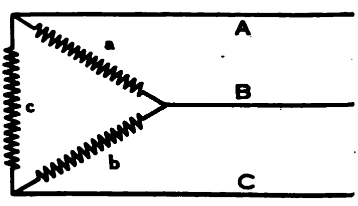


FIG. 635.—Three-phase armature windings connected in Δ.

It will be observed that the Y connection, Fig. 632, is a kind of series connection as far as any two phases are concerned and therefore delivers the greatest voltage from a given number of armature conductors. The Δ connection, Fig. 635, is a kind of multiple connection and therefore delivers a greater current at a lower voltage for a given number of armature conductors. Any three-phase winding may be connected up in either Y or Δ. The actual connections on a given machine can only be deter-

mined by inspection. Thus if the lead A', Fig. 636, be traced into the machine, it will be found to divide into the two circuits I and F, while if the lead A', Fig. 630, be traced back into the machine it will be found to enter the conductor F without branching. If the machine is provided with a single series winding the division of the circuit in the former case would indicate a Δ connection while the fact that it does not branch in the latter case would indicate a Y connection. It is important to note

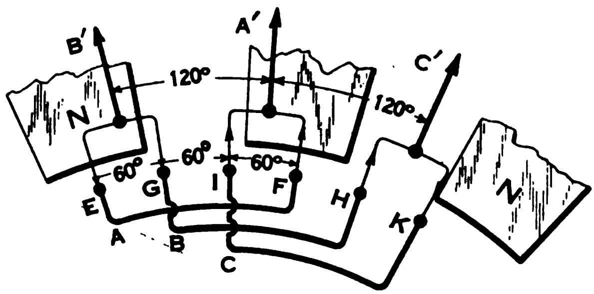


FIG. 636.—Relative location of winings comprising three separate phases when connected in Δ.

that no possible test of resistance through the windings from the external wires A', B' and C' will give an indication of whether the machine is connected in Y or in Δ.

Types of Alternator Windings

All alternator armatures are provided with windings of the drum type, with the active portion of the conductors placed in slots.

As to the mechanical arrangement of the coils the windings may be divided into three general classes:

First: Basket windings.

Second: Concentric windings.

Third: Two-layer windings.

Any type may have several convolutions per coil or a single winding unit or bar.

The ends of bar conductors or coils may bend away from each other, which is the characteristic arrangement with a wave winding, or the end connections may both bend in the same direction, which is the plan with a lap winding. Thus, as in direct-current machines, both wave and lap windings may be employed

Any of these windings may have one or more slots per phase per pole, one slot giving a concentrated and two or more slots a distributed winding.

The basket winding is pictured in Fig. 637. It is adapted for very small low-voltage induction motors only. It is a special form of concentric winding in which all of the coils are of the same shape and length and therefore of the same resistance.

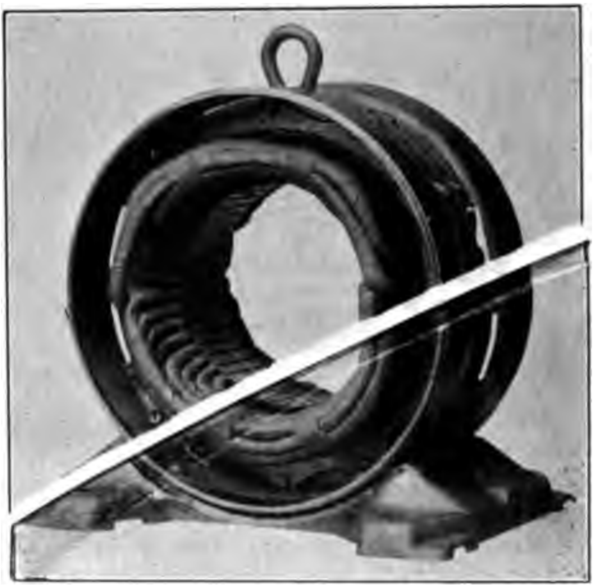


FIG. 637.—"Basket" winding used by Westinghouse Company for small alternating-current motors.

Like the concentric winding it has but one-half of a coil per slot, and there are therefore one-half as many coils as slots in the machine.

The concentric winding has but one bunch or layer of conductors in a slot. The coils interlink each other on the end, in this particular resembling a chain. As half of one coil fills a slot there are half as many coils as slots. The end connections for these coils are widely separated from each other, thus admitting of an abundance of insulation. This adapts the winding particularly for high-voltage machines.

The disadvantage of a concentric winding is that all of the coils are not alike in shape or in length. The manufacturing cost

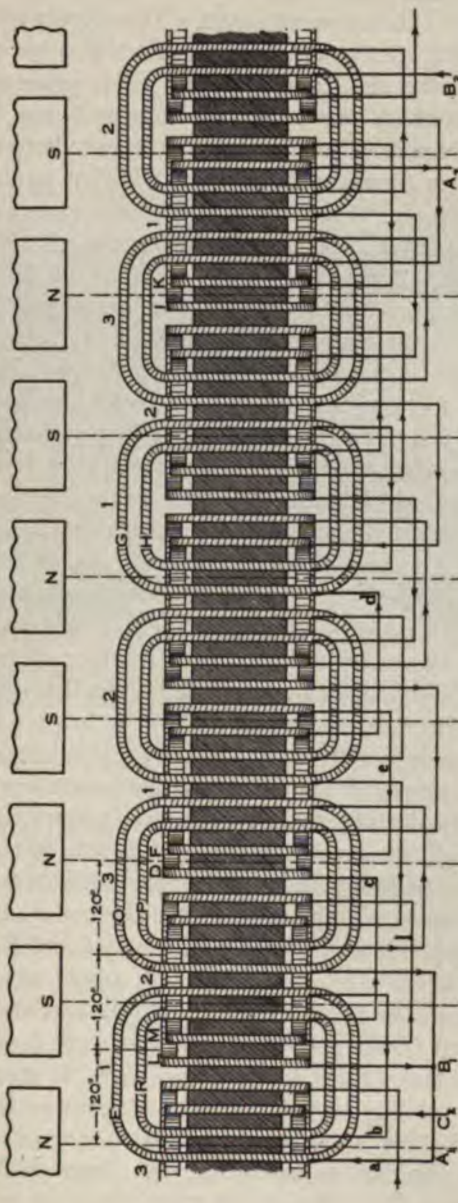


FIG. 639.—Concentric winding and connections for three-phase alternator.

is therefore high and the coils of unequal resistance. In Fig. 639 there are two styles and four separate sizes of coils, consequently four different resistances. This disadvantage is not a serious one for the four different sizes are taken in order for each phase so that the total resistance for each phase is the same. The order in which the coils are connected and the relative directions of e.m.fs. should be carefully studied in Fig. 639. In this figure is shown a distributed winding having two slots per phase per pole. Starting from the common connection of the Y at the point B_1 and progressing to the left via the wire a, the circuit passes upward through the outer coil E of phase one, which is to the left of the center of a north pole in the field. The circuit leads back to the right of the center of the next south pole. Had this coil exactly spanned the dotted lines from the center of one north to the center of the next south it would have constituted a **full pitch** winding. As it is, the span of the coil is somewhat greater and therefore constitutes a **fractional pitch** winding. The coil R within this one has a span somewhat less than a full pitch. This is called a **short pitch** coil. Such coils have a very advantageous effect in smoothing out the irregularities of the induced e.m.f. wave and make it approach more closely to the form of a sine wave. After the circuit has been completed in the outer coil whatever number of times the convolutions require, the current is led over the wire b into the inner coil R which is telescoped within the larger. The average of these two coils is a full pitch of 180°. Having completed the circuit in the inner coil the current passes via the wire c into the coil D which is of different shape but which bears the same phase relation at a given instant to the next N pole to the right as the coil E bore to the field pole N. Having completed the circuit of D the current passes via the wire e into the coil F, thence via the wire d, through G and H, thence through I and K, terminating at the point A_2. This completes one phase of the winding. Commencing at the point B_1 at the middle of the Y, the circuit may be traced directly upward into the coil L and thence in series via the wire l into the coil M. Now the average distance from the dotted line between these two coils to the dotted line between the two coils, E-R, is 120°. The circuit continues through the winding, maintaining this phase relation throughout to the point B_2. The circuit may similarly be traced from

the common point via the wire C_1 and the coils O-P through the winding to the terminal C_2. It will be observed that the average distance from between the coils O-P to the line between the coils L-M is likewise 120°. Thus a three-phase symmetrical winding is obtained in which the voltages generated follow each other 120° apart in an external circuit of three wires to which the armature windings may be connected either in Y or in Δ.

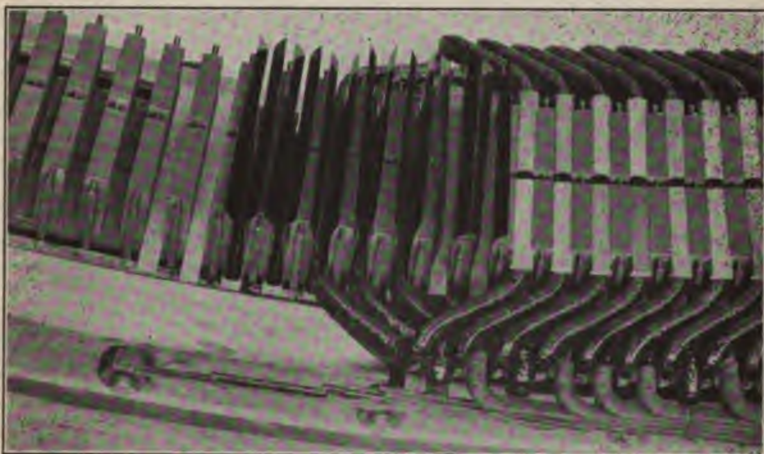


FIG. 640.—Two-layer armature winding for alternator showing method of nesting coils. All coils of this construction are of the same size.

In two-layer windings each slot has two groups of conductors and there are therefore as many coils as there are slots. The term **two-layer** does not refer to the number of layers of conductors but to the arrangement of the coils themselves in the slot. Fig. 640 illustrates a two-layer winding. An advantage of this arrangement is that all of the coils are the same form, size and resistance. This results in a perfectly symmetrical winding. The shape of the coil is similar to that employed on direct-current machines with two-layer windings. If several convolutions per coil are employed the coil is wound on a form and taped up as a separate unit. An advantage of the two-layer winding is that a large number of coils and slots may be employed. It is widely used for alternators, for induction and synchronous motors. In fact it has practically superseded the

concentric winding for all alternating-current machines with the exception of small induction motors. While the ends of the coils cannot be so widely separated as in a concentric winding, the shape is such that the necessary insulation can be provided.

An important fact which must always be borne in mind with reference to this winding is that a high voltage is impressed between the half coils in the top and those in the bottom of a slot. Therefore the insulation must be heavy and thorough. As each coil is individually insulated this naturally provides a double thickness of insulation between the coils. While more space is thus required in a slot for insulation than with a concentric winding, the symmetrical coils of uniform resistance are of sufficient advantage to more than offset the disadvantage of the extra space required.

For a given e.m.f. between line wires, fewer convolutions per phase will be required in a Y than in a Δ connection. Therefore a smaller amount of slot space is occupied by insulation and from this standpoint Y connections are preferable to Δ.

With a Δ connection the phases form a closed circuit within the machine and if the e.m.fs. are unbalanced a local current may circulate in the circuits established, thus causing excessive heating.

A distributed winding may be connected for delivery of two phase power instead of three-phase. Thus if the conductors *G* to *H* in Fig. 609 are divided into two groups bearing the relation of *A* to *B* and therefore differing in phase by 90° these two groups may be connected to separate external circuits as shown in Fig. 617. The entire output of one phase could then be drawn over the wires *A*-*B* and the entire output of the other phase over the wires *C*-*D*. These two phases could be used to supply a lamp load or motor load or both. If a motor load is to be operated the wires *B* and *C* are often merged into one at the alternator and at the motor, making a two-phase, three-wire transmission. This really produces a three.phase, three-wire system, although not with the same symmetrical distribution of currents and voltages obtained in Fig. 632. Early polyphase systems were designed two-phase. The operation of a three-wire system effected something of a saving in copper. Practically all modern polyphase systems, however, are symmetrical three-phase, three-wire systems as illustrated in Fig. 632.

Fig. 641 illustrates a three-phase, six-pole armature winding having three slots per phase per pole and therefore 54 slots. The coils of each phase occupy 18 slots. Each slot contains two layers or half coils. The 18 coils of each phase are connected

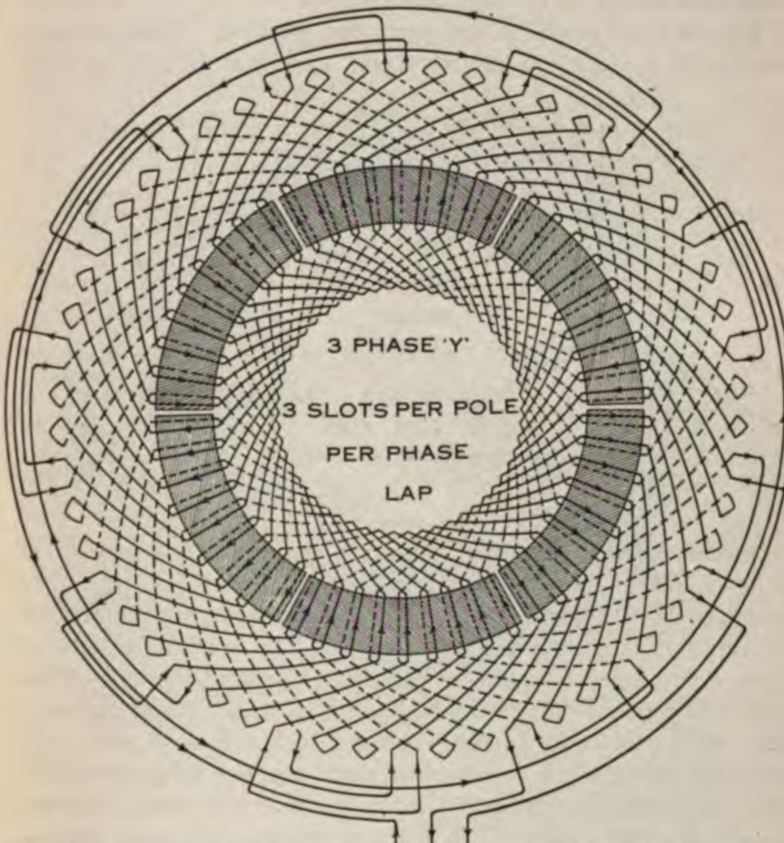


FIG. 641.—Three-phase distributed, two-layer winding for 6-pole Y-connected alternator armature.

in series. The half coil occupying the top of the slot is shown in solid lines and the half of another coil occupying the bottom of the same slot is shown in dotted lines. Each coil is shown as consisting of but one convolution. It may, however, contain any number of turns. This is a two-layer formed coil, lap winding. The three separate phases may be connected either in Y or in Δ. The diagram represents a Y connection. Thus in Fig.

642 the corresponding terminals of each phase, A_2, B_2 and C_2, are tied together at the common or middle point of the Y, while the other ends, A_1, B_1, C_1, lead to the outside circuit. Fig. 643 shows how the phases would be reconnected for Δ. Thus A_1 is connected to C_2, C_1 to B_2, B_1 to A_2.

Fig. 644 represents a two-layer bar winding. Each element consists of a single bar insulated and with its ends bent in oppo-

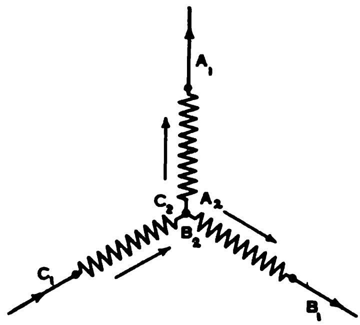


FIG. 642.—Y connection of armature winding, shown in Fig. 644.

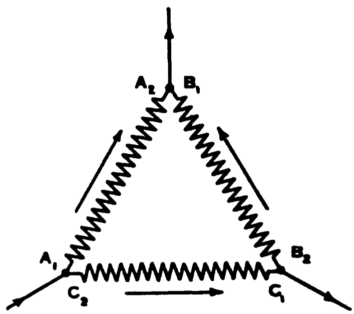


FIG. 643.—Δ connection of armature winding, shown in Fig. 644.

site directions. Thus this becomes a wave winding instead of a lap winding. The bar constituting one element in the top of a slot is shown in solid lines while the bar occupying the bottom of the slot is shown in dotted lines. The successive bars of each group are connected by conductors around the end of the stator as shown. This winding has two slots per phase per pole, thus for 8 poles and 3 phases it has $2 \times 3 \times 8 = 48$ slots. As each slot contains two conductors there are 96 conductors in all. The terminals A_1, B_1 and C_1 leading into the three separate phases are 120° apart. This winding is commonly used for low voltage and large current output. Both of the circuits shown in Fig. 641 and Fig. 644 should be carefully traced to get a proper conception of the development of each of these two forms of winding.

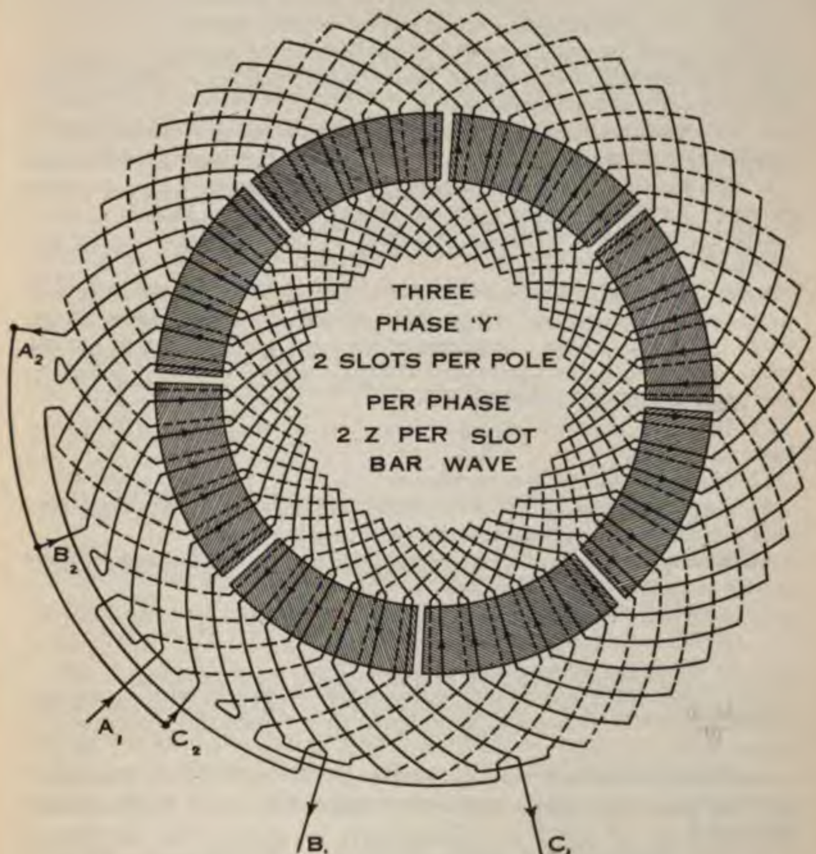


FIG. 644.—Three-phase, two-layer, bar winding, for 8-pole, Y-connected alternator armature.

SECTION XIV CHAPTER VII

ALTERNATING CURRENTS

CONSTRUCTION OF ALTERNATORS

1. Distinguish between monophase and polyphase alternators.

2. Why are practically all alternators constructed polyphase?

3. Distinguish between concentrated and distributed windings.

4. What are the advantages of concentrated windings? What are the advantages of distributed windings?

5. To what extent are the windings of modern alternators distributed?

6. How are alternators excited and how are the exciters mounted and driven?

7. Mention the three types of alternators with respect to the revolving member. Explain the construction and advantages of each type.

8. What form of construction is almost universally adopted in modern alternators?

9. Sketch several poles of an alternator field. Sketch an armature coil under each. Connect these coils so that their e.m.fs. will be properly added.

10. An alternator with a concentrated armature winding generates 11,000 volts. What would be the generated voltage if the same number of conductors were used in a fully distributed winding?

11. What are the three causes of loss of potential in an alternator as it takes its load?

12. How may the first loss be reduced?

13. Explain fully the effects of self-induction in an armature winding. How does it influence the voltage delivered by the machine?

14. Explain the effects of armature reaction upon the field flux and delivered voltage in an alternator armature:

(*a*) When the current is in phase with the e.m.f.

(*b*) When the current lags behind the e.m.f.

(*c*) When the current leads the e.m.f.

15. Explain the phase relation between the conductors on a three-phase armature and their relation in the external circuit when the winding is connected in Y.

16. Explain the phase relation between the conductors on a three-phase armature and their relation in the external circuit when the winding is connected in Δ.

17. Give diagrammatical sketch of a Y-connected alternator. Show by three curves, the proper phase relation between the currents in the different wires?

18. Give diagrammatical sketch of a Δ-connected alternator. Show by three curves, the proper phase relation between the currents in the different wires.

19. Explain the plan of a "basket" winding. Upon what kind of machines s it used?

20. Explain the plan of a "concentric" winding. What are its advantages and for what type of machines is it particularly adapted?

21. Explain the plan of a "two-layer" winding. What are its advantages and for what type of machine is it particularly adapted?

ALTERNATING CURRENTS

A. C. TRANSMISSION SYSTEMS

Among the various possible systems for transmitting power the oldest and simplest is the two-wire, single-phase system, Fig. 645. Here is represented the stationary armature winding of an alternator connected to two line wires which transmit power either for lighting or motors any desired distance.

The initial pressure on such systems was 1,100 volts. Improved apparatus is now available for generating as high as 13,200 volts. If higher voltages are deemed desirable they can easily be obtained by employing raising transformers which can be arranged to raise the pressure anywhere up to 220,000 volts.

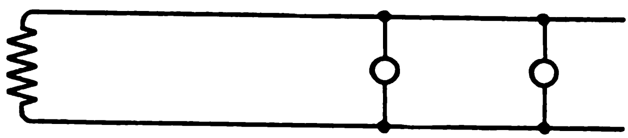


FIG. 645.—Two-wire single-phase system.

The advantage of the single-phase system is its simplicity. The problem of balance, which is always involved with systems using more than two wires, is not encountered.

The advantages of high voltage for transmission of power should be emphasized. The first and most important law governing the transmission of power is the following:

For transmitting a given amount of power, a fixed distance, with a fixed loss, the copper required varies inversely as the square of the voltage of transmission. Thus, if **10 kilowatts** were to be transmitted one mile, under a transmitting pressure of **100 volts,** the permissible loss being fixed at 10%, and the copper required was **32,000 pounds,** then to transmit the same **10 kilowatts** the same distance with the same loss at **200 volts** would require but **8,000 pounds** and to transmit the same power at same distance with the same loss at **1,000 volts** would take but **320 pounds.** That is to say, if the voltage of transmission is doubled the copper required is quartered. If the voltage of

transmission is made ten times as great, the copper required is but one-hundredth of the amount previously called for.

This emphasizes the importance of transmitting power at the very highest practical voltages. It does not follow, however, that the voltage of transmission can be indefinitely raised, for as the voltage is increased the difficulties encountered and the expense involved for insulation also increase and at voltages of 100,000 and upwards they become formidable. So it comes about that the excessive cost for insulation may eventually more than offset the value of the copper saved, and when that point is reached there is no advantage in further increasing the potential of transmission. In late years the high point in transmission of power has been in the vicinity of 150,000 to 165,000 volts. In 1920 transformers were built and transmission lines designed which made 220,000 volts possible.

Another interesting feature of high voltage transmission is the bearing which the **voltage impressed** has upon the **total copper** required. This may be stated as follows:

If the voltage of transmission be increased in direct proportion to the distance through which it is desired to transmit a given amount of power with a fixed percentage of loss, then the amount of copper required is independent of the length of transmission. Thus, if 10 kilowatts were to be transmitted one mile with a 10% loss at a transmitting pressure of 100 volts and 32,000 pounds of copper were required, then if the distance was increased to 2 miles and the transmitting voltage raised to 200, or the distance was increased to 10 miles and the transmitting voltage raised to 1,000, precisely the same 32,000 pounds of copper would serve in every case and the total loss in the line in each case would be 10% of the generated power.

In order that power may be transmitted economically it is well to allow approximately 1,000 volts at the alternator for every mile of transmission. This may be laid down as a rough approximation to good engineering practice with the exception that for distances of the first mile or two not less than 2,200 volts is employed. Thus a 6-mile transmission would be operated at 6,600 volts and an 11-mile transmission at 11,000 volts, a 110-mile transmission at 110,000 volts and a 220-mile transmission at 220,000 volts.

Every system for transmitting power which **economizes copper** at a given voltage **always involves** the **problem of balance** in

some form. The earliest and simplest of the systems for saving copper is the three-wire system devised by Edison. While primarily designed for direct-current operation it is equally applicable to the alternating-current system. Fig. 646 illustrates the plan. Here the stationary winding of an alternator armature *A-B* has fixed terminals from which the two-line wires *E-H* extend. From a middle point in this winding a tap *C* is taken. For the same voltage at the lamps the voltage of transmission will be double that shown in Fig. 645. When the transmitting voltage is doubled the copper required is quartered for a given loss and fixed distance with equal voltages

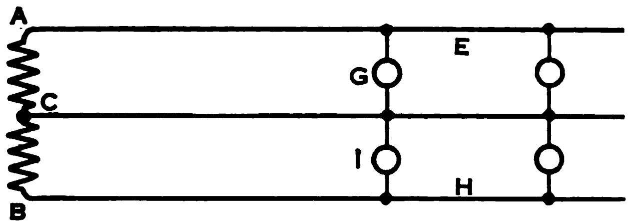


FIG. 646.—Three-wire single-phase system.

at the lamps. Thus the wires *E-H* would be one-fourth the size of the two outside wires in Fig. 645, but in order that the lamps at *G* may be disconnected independently of the lamps at *I*, a neutral wire one-half the size of the other wires must be provided. The addition of this third wire makes the net copper required 31.25% of that of the two-wire alternating system. The load must be equally balanced between the two sides of the system *G* and *I*. Any unbalanced load or excess on any one side over the other will require the same copper as for the two-wire system. As there is nothing to hinder the raising of the voltage of the two-wire alternating current system to practically any extent, the desired economy in copper shown in Fig. 646 could be brought about in the two-wire system by simply raising the voltage from 2,200 to say 6,600 or 11,000 if necessary by means of transformers. The problem of balancing the load between the two sides of the system would then be eliminated and the neutral wire would not be required to effect the saving in copper shown in Fig. 646.

Thus single-phase alternating-current systems are generally operated two wire as far as the transmission line is concerned.

After passing through the reducing transformers the low-tension system is practically fixed at 110 volts for the lamps. Now by employing 220 volts and the three-wire system, 110-volt lamps may be operated on each side and the advantage of three-wire distribution with its consequent economy in copper may be fully realized. Hence in secondary networks for lighting, the three-wire, 220-volt system prevails.

The two-phase, four-wire system is illustrated in Fig. 647. Here phase A is led through fixed terminals to the external circuit C-D, while phase B leads independently to the circuit E-F. This system was devised first, because of the greater output of an alternator when so operated compared with its

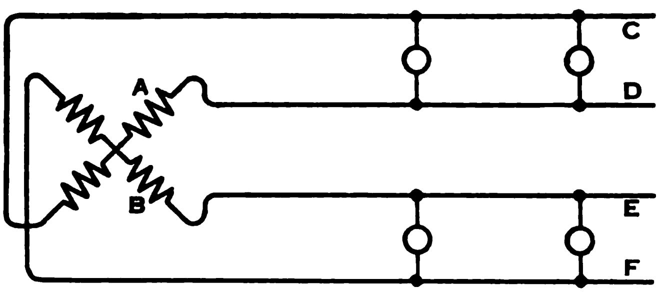


FIG. 647.—Four-wire two-phase system.

single-phase output, and second, because of the ability to operate motors which could not at that time be automatically started upon a single-phase system. In the plan shown there is an entire independence of the two phases. If each of the two wires in Fig. 645 weighed 100 pounds then each of the four wires in Fig. 647 would weigh 25 pounds. Thus the copper required would be the same as for a single-phase system and half the load would be transmitted on each phase.

Fig. 648 represents the two-phase, three-wire system. Here the two phases A and B are connected together at the common point C. The two main wires of the system are E and F while the wire G forms a neutral. The load is connected equally between the wires E and G and F and G. If the voltage on the lamps, that is the voltage of phases A and B, are the same as in Fig. 647, the copper required for this system is 72.8% of that required in the operation of a single-phase, two-wire system. This

system is used chiefly for the operation of motors, where there is no particular advantage in keeping the phases separate.

All of the early self-starting induction motors were designed for two-phase systems. Subsequently it was found that the three-phase system had a distinct advantage in the copper required for transmission and there was no corresponding dis-

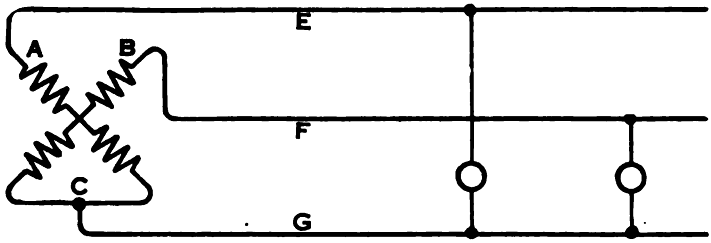


FIG. 648.—Three-wire two-phase system.

advantage. In late years practically all of the polyphase installations have been made three-phase. The plan is illustrated in Fig. 649. Here the terminals of the separate phases *A*-*B* and *C* lead to three-line wires. The other ends of these three phases connect together at a common point. To get the full

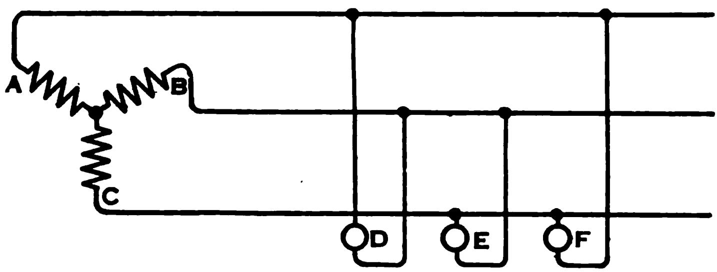


FIG. 649.—Three-wire three-phase system.

benefit of the economy in copper effected by this system the load should be equally distributed between the three phases as at *D*, *E* and *F*. The voltages between any two-line wires is the same. The copper required for the same voltage at the load is 75% of that required for the two-wire, single-phase system. Thus if each of the four wires in Fig. 647 weighed 25 pounds, each of the three wires in Fig. 649 would weigh 25 pounds and the fourth wire would be saved entirely. Furthermore, this would be without any corresponding disadvantage

save that the load would have to be balanced between three sides of the system instead of between two.

There is another three-phase system involving four wires shown in Fig. 650. Here a "balance wire" leads from the middle point of the Y and extends throughout the entire distributing net work. The load is connected equally between the three principal wires of the system and this balance wire. For the same voltage at the lamps only 29.2% of the copper required on the single-phase two-wire system is necessary for all four wires. This is because the combined advantages of the three-wire

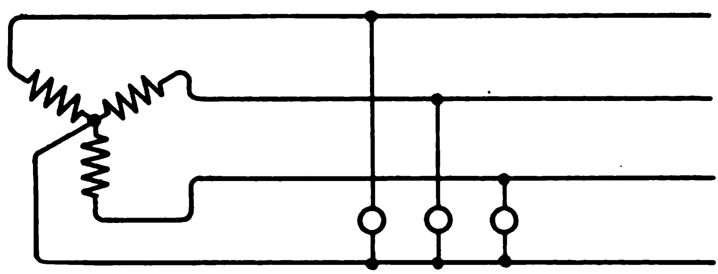


FIG. 650.—Four-wire three-phase system.

system and the inherent saving of the three-phase system are simultaneously obtained. This system, however, is not widely used for the same reason that single-phase transmission systems are not operated three-wire. As the transmitting voltage is practically unrestricted, the necessity for balancing more than offsets the advantage of economy in copper, especially as an increase in transmitting voltage, will effect the same reduction in copper.

A. C. Potential Regulators

Since the invention of the incandescent lamp the problem of voltage regulation has been one of prime importance to the electrical industry. Engineers of the highest ability have concentrated their efforts on the solution of the problem. Through the efforts of such men as Thury, Carpentier, Edison, Chapman and Tirrill, most excellent systems have been produced. Many regulating devices have been tried and found unsatisfactory. Among those which have survived, one of the most widely used for the control of both direct and alternating-current systems

is the Tirrill regulator. The principle of the Tirrill regulator was first employed in a system invented by Edison, but with the crude equipment available at that time it was not possible to produce a successful regulator.

The need for an alternating-current voltage regulator is much greater than that for a direct-current regulator because of the large and complex alternating systems in operation. The automatic regulation of alternators presents an unusually difficult problem, the principal one being the inherent tendency of the e.m.f. in an alternating-current generator toward hunting caused by the inductance of the alternator field winding.

It might be supposed at first glance that a direct-current regulator could be applied directly to an alternating-current machine by simply connecting the control magnet across the alternating-current mains and using a relay to short-circuit the exciter field rheostat. This is unsatisfactory, however, for several reasons. In the first place assume that the relay contacts across the exciter rheostat are closed and that the system is in the act of building up. The instant the line voltage reaches its proper value, the main control magnet opens its contacts against the tension of its spring, thereby opening the relay contacts and causing the exciter to begin to build down. The alternating voltage, however, does not stop building up at this instant, since the exciter voltage is considerably in excess of the voltage necessary to force the current through the generator field resistance. Now the exciter voltage gets considerably in advance of the generator field current, because, in the act of building up the exciter is compelled to supply a voltage equal to the drop in the alternating-current generator's field resistance plus the inductive drop or counter e.m.f. due to the increase in flux through the field winding. This inductive drop increases directly with the rate at which the exciter builds up. It is evident therefore that at the instant the line voltage has reached normal, the exciter voltage is in excess of the value necessary to maintain the required line voltage by an amount equal to the inductive drop in the generator field. The alternator voltage therefore continues to rise above normal for some time notwithstanding the fact that the relay contacts across the exciter rheostat are open. When the alternating voltage drops to normal and the main contacts close, the exciter voltage is far

below normal. The voltage is therefore carried continually above and below its proper value. The system is thus inoperative due to hunting.

An alternative plan is to let the relay contacts short-circuit the rheostat in the alternator's field. By this method hunting would be avoided, but in a machine of any size the field currents are too large to be handled.

From the foregoing it will be seen that it is impractical to regulate the voltage of an alternating-current system by means of a single main control magnet energized from the alternating voltage whose contacts directly control the exciter. Some additional link or coupling is necessary to bridge the generator inductance. This was accomplished by carrying the stationary contact of the alternating control magnet, on the lever arm of a second magnet energized from the exciter. The second or anti-hunting magnet is really a complete direct-current regulator whose voltage is adjusted by the magnet energized by the alternator's voltage. This combination of two cooperating magnets, one responding to the alternator's voltage which is to be regulated, and the other to the exciter itself, was conceived and developed by Tirrill.

This regulator involves **an alternating-current magnet which adjusts the voltage for which the direct-current magnet regulates.** Fig. 651 shows the circuits in one of the simplest forms of regulators built on this principle. Here a D. C. control magnet *D.C.M.* is connected directly through an adjustable resistance *R* to the exciter bus bars, *X-Y*. This magnet has a fixed core in the bottom and a movable core in the top attached to the pivoted lever on the opposite end of which is carried one of the two main floating contacts *M.C.*

An A. C. control magnet, *A.C.M.*, responsive to line potential, is supplied through a potential transformer *P.T.*, from one phase of the three-phase system. The core of this magnet is attached to one end of a counter-weighted lever, the pull of the A. C. magnet on the core being upward. The other end of the lever carries one of the floating main contacts, *M.C.* The downward pull on the core of this magnet by gravity tends to close the main contacts; the upward pull due to the magnetizing effect of the coil plus the counter-weight *K* tends to open the contacts.

The floating contacts *M.C.* control *A*, one of two windings of a differentially wound relay. The other relay winding *B* is

permanently connected across the exciter bus bars. The relay contacts *R.C.* are connected across the exciter field rheostat terminals. The condenser *Z* cares for sparking that may occur at these contacts.

The operation of the regulator is as follows

First, open the shunt across the exciter field rheostat, *E.F.R.*, by the single pole switch *S*.

Second, adjust the exciter field rheostat until the A.C. voltage is 65% below normal. This weakens the alternating-current

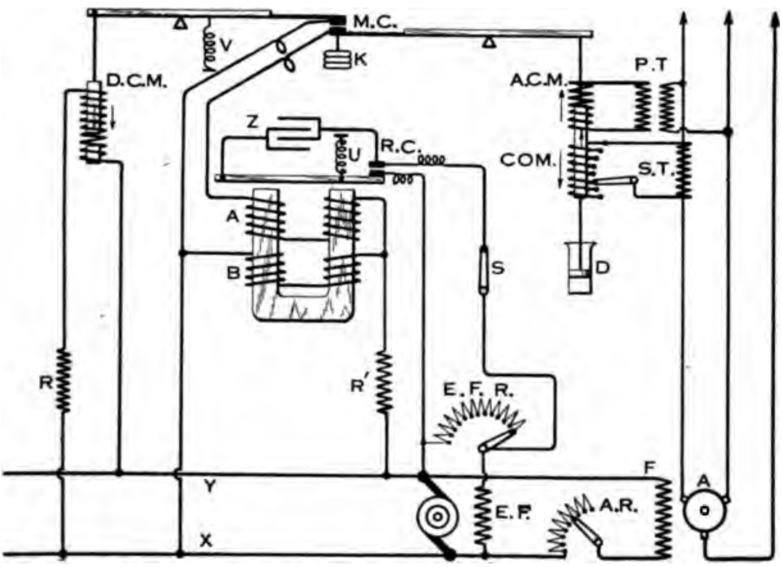


FIG. 651.—Tirrill alternating-current voltage regulator.

magnet *A.C.M.* and allows its core to fall by gravity, thus closing the main contacts *M.C.*

The D. C. control magnet *D.C.M.* has also been weakened through the lowered exciter voltage and the spring *V* pulls down on the lever, thus closing still more firmly the main contacts *M.C.* These main contacts put in circuit the winding *A* of the differential relay, the winding *B* being already in circuit. As these two windings are connected differentially, the armature is released and the spring *U* closes the contacts *R.C.*

Third, close switch *S*, thus short-circuiting the exciter rheostat *E.F.R.*

The exciter voltage now rises. *A.C.M.* and *D.C.M.* become stronger and at the e.m.f. for which these magnets have been previously adjusted by means of counter-weight *K*, the main contacts, *M.C.*, open. This opens the winding *A* of the relay. The winding *B* thus becomes operative, the relay attracts its armature breaking *R.C.*, which again cuts the exciter field rheostat *E.F.R.* into circuit and the e.m.f. begins to fall.

The D. C. magnet *D.C.M.* is very sensitive and the above cycle of operation is effected at a high rate of speed and the contacts *M.C.* vibrate rapidly.

The effect of the self-induction of the alternator's field *F* is overcome in this way: As the voltage begins to climb with the contacts *R.C.* closed, *A.C.M.* raises its core in the effort to break *M.C.* As the exciter's voltage is ahead of the alternator's voltage, however, *D.C.M.*, responsive to this advance voltage, pulls down on its core and raises the upper of the contacts *M.C.*, thus **anticipating the moment of break** by an amount sufficient to **offset the lag due to self-induction** of the alternator field.

Conversely, when the voltage commences to fall due to the insertion of the exciter's field rheostat the self-induction of the alternator's field sustains the current and the contacts *M.C.* would not close soon enough were it not for the fact that the exciter's voltage going down in advance of the alternator's voltage weakens *D.C.M.* so as to lower the upper contact of *M.C.* and anticipate the time when these contacts shall close beyond the point where they would close if actuated by *A.C.M.* only. The regulator thus holds the voltage very closely and the difficulty due to the loose coupling between the exciter's voltage and the alternator's voltage is overcome.

The dash pot *D* prevents the vibration of the core of the A. C. magnet due to the alternating current and also tends to check hunting.

The addition of a coil, *COM.*, to the regulator enables it to give the system the characteristics obtained with a compound wound generator. This winding is supplied from a series transformer *S.T.* and is energized in proportion to the load current. The winding is connected so that it opposes the potential winding. Thus, as the load increases, the strength of this winding increases. Now the potential winding *A.C.M.* tends to raise

core, break the contacts *M.C.*, and thus check the rise in potential. The compensating winding *COM.* pulls downward on the core, thus opposing the operation of the potential winding. This tends to prevent the opening of the contacts *M.C.* and allows the potential to rise further. As this winding is energized in proportion to the current flowing to the load, the rise in potential permitted by the regulator is in exact proportion to the load. By means of a commutating switch shown, the number of convolutions in this winding may be adjusted so that the compounding can be set at anywhere from 1 to 15%. By a suitable arrangement of inductance and resistance in the main line supplying the compensating winding the regulator may be made to compound for loads having various power factors.

As the load varies on the system the potential generated must vary. Thus with a heavy load the generated voltage must be higher than with a light load. This means that the contacts *M.C.* must be maintained closed and the exciter field rheostat short circuited for a longer period in the cycle than with a light load. To accomplish this the main contacts are carried on flexible supports and the ratio of the time that the contacts are closed to the time they are open is determined by the level at which these contacts float. With a heavy load the compensating winding tends to pull down on the core of *A.C.M.*, thus carrying the lower contacts of *M.C.* at a higher level and prolonging the short circuit on *E.F.R.* for a greater period.

For power stations generally, either small or large, there is but one pair of main contacts. These are operated jointly from one A. C. magnet supplied by the A. C. bus bars and one D. C. magnet supplied by the exciter bus bars. These main magnets *M.C.* are connected to operate anywhere from two to twelve relays according to the size of the station. Each relay instead of short-circuiting the whole of an exciter's field rheostat is made to short-circuit such a portion thereof as its contacts *R.C.* can conveniently handle without burning. These sections can be broken up so that the potential difference across each pair of relay contacts is sufficiently low to be satisfactorily cared for. This arrangement is essential in large power systems. Separate relays may also be employed to care for the field rheostats of separate exciters working in parallel upon the same bus-bar system, but one main regulator holds the voltage of the entire station steady.

SECTION XIV | CHAPTER VIII

ALTERNATING CURRENTS

A. C. TRANSMISSION SYSTEMS

1. Explain the single-phase two-wire system. What are its advantages and limitations?

2. What is the effect of increasing the voltage of transmission, upon the copper required for transmitting a given amount of power a specified distance with a fixed loss?

3. What is the effect of the voltage employed, upon the total amount of copper required for transmitting a given amount of power an indefinite distance with a fixed loss?

4. Explain the three-wire single-phase system. What are its advantages and disadvantages? What is the amount of copper required for a given percentage loss in transmission, compared with a single-phase system?

5. Sketch and explain the two-phase four-wire system. What are its advantages and disadvantages? What is the amount of copper required compared with a single-phase system?

6. Sketch and explain the two-phase three-wire system. What are its advantages and disadvantages? What is the amount of copper required compared with a single-phase system?

7. Sketch and explain the three-phase three-wire system. What are its advantages and disadvantages? What is the amount of copper required compared with a single-phase system?

8. Sketch and explain the three-phase four-wire system. What are its advantages and disadvantages? What is the amount of copper required compared with a single-phase system?

9. Explain in detail the Tirrill alternating current regulator. Explain fully how the time lag due to the self-induction of the alternator's field is overcome. How is the regulator made to compound or overcompound the alternator?

10. How is the exciter field current handled for large size units?

ALTERNATING CURRENTS

POWER IN POLYPHASE SYSTEMS

If the e.m.fs. A-B and A-C, Fig. 652, in a two-phase machine, are always equal in magnitude and 90° apart in time phase, the sum of the voltages is equal to $\sqrt{AB^2 + AC^2}$. If A-B = 1 and A-C = 1, then B-C = $\sqrt{1^2 + 1^2} = \sqrt{2}$. If A-B and A-C equal 5, then B-C = $\sqrt{2} \times 5$. Thus the geometric sum of the voltages of two equal windings 90° apart in time phase will always be $\sqrt{2}$ times the voltage of one phase. Thus if in Fig. 653 a two-phase machine is connected three-wire as shown and the voltage of each phase is 100, the voltage across the two wires A-B will be the $\sqrt{2} \times 100$, or 141 volts. If the current in each of the outside wires A-B, Fig. 653, is 10 amperes, then the current in the middle wire C will be $\sqrt{2} \times 10 = 14.1$ amperes. Where the **voltages** of two phases merge into a resultant 90° apart, the **combined voltage** is $\sqrt{2}$ times **one of the components.** Where the **currents** of two phases merge into a common wire, the **total current** is $\sqrt{2}$ **times one of the components.** This, of course, assumes a balanced load on the two sides of the system and a power factor of 100%.

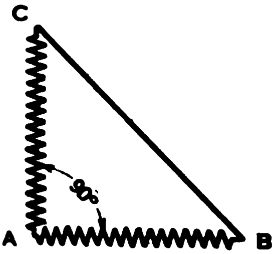


Fig. 652.—E.m.f. of two phases 90° apart when connected in series.

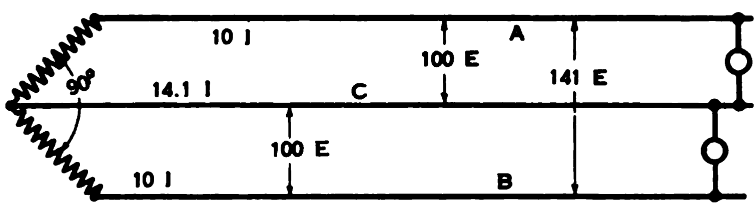


Fig. 653.—Relative e.m.fs. and currents delivered by a two-phase machine when connected to a three-wire circuit.

There are two methods by which the power in a **two-phase** system may be measured:

First, by one wattmeter as in Fig. 654. Here the current coil is put in the middle wire between the two phases, and the potential coil is connected on one end to the same wire and on the other end to the wire A. After observing the readings on this side, the potential terminal at A may be switched to the terminal at B. The sum of the two indications is the total power.

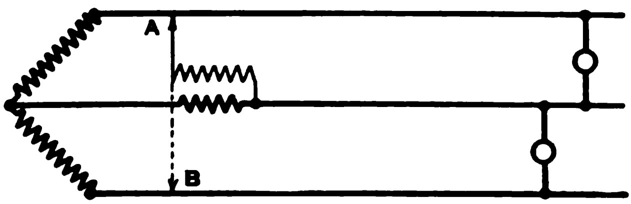


FIG. 654.—Measurement of the power in a two-phase, three-wire circuit by means of one wattmeter.

Second, the more general connection for two-phase measurement is shown in Fig. 655. Here two wattmeters are connected, each with its current coil in one of the outside wires and one end of each potential coil connected to the same wire, while the remaining terminals of the potential coils are connected to the middle wire which contains no current coil. The sum of the two readings will be the total power.

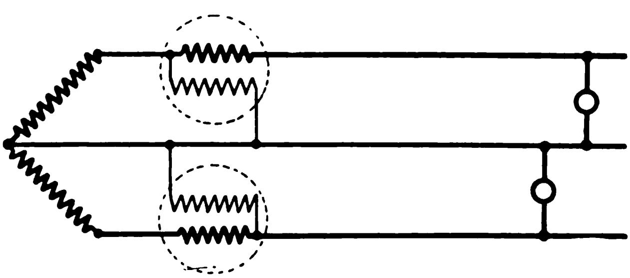


FIG. 655.—Measurement of the power in a two-phase, three-wire circuit by two wattmeters.

With a **three-phase** machine connected in Y the e.m.f. between any two line wires equals the e.m.f. of one phase multiplied by $\sqrt{3}$. This comes about from the fact that from trigonometry it may be stated that the voltage V, Fig. 656, due to two phases in series 120° apart, is to the sine of the angle opposite it, which is 120°, as the voltage of one phase, A, is to the sine of the angle

opposite it, which is 30°. Now the sine of 120° is the same as the sine of 60°. Thus

$$\frac{V}{A} = \frac{\sin 120°}{\sin 30°} = \frac{\sin 60°}{\sin 30°} = \frac{0.866}{0.500} = 1.732 = \sqrt{3}.$$

Therefore $\frac{V}{A} = \sqrt{3}$ and $V = A \times \sqrt{3}$.

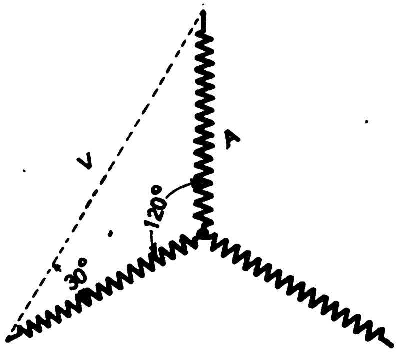


FIG. 656.—Voltage delivered by two phases 120° apart when connected in series.

The relation of the voltages, currents and power in the separate phases to the total power of the system for both Y and Δ connections will now be considered. In this discussion

p = watts per phase.
P = total power in system.
E = e.m.f. between any two line-wires.
e = e.m.f. of one phase.
i = current per phase.
I = current in each line wire.

For a Y connection, with a 100% power factor—

$$E = e \times \sqrt{3} \quad (1) \qquad i = I \quad (3)$$

$$e = \frac{E}{\sqrt{3}} \quad (2) \qquad p = e \times I \quad (4)$$

$$p = I \times \frac{E}{\sqrt{3}} \quad (2 \text{ and } 4)$$

$$P = 3 \times p = 3 \times I \times \frac{E}{\sqrt{3}} = \frac{\overset{\sqrt{3}}{\cancel{3}} \times I \times E}{\cancel{\sqrt{3}}} \quad (5)$$

$$P = \sqrt{3} \times I \times E \quad (6)$$

From this it will be seen that the total power in a three-phase system is **not** the current in each of the three-line wires multiplied by each of the voltages and then summed, but the **current** in a **single-line** wire multiplied by a **single voltage** and this product multiplied by the **$\sqrt{3}$ factor.** The power in a three-phase system is always equal to the sum of the power in the three separate phases. Thus in Fig. 657, if the current per phase is 10 amperes and the voltage per phase is 1,000 volts, then the power per phase is 10,000 watts. This multiplied by 3 for the three phases = 30,000 watts. The voltage between line wires is

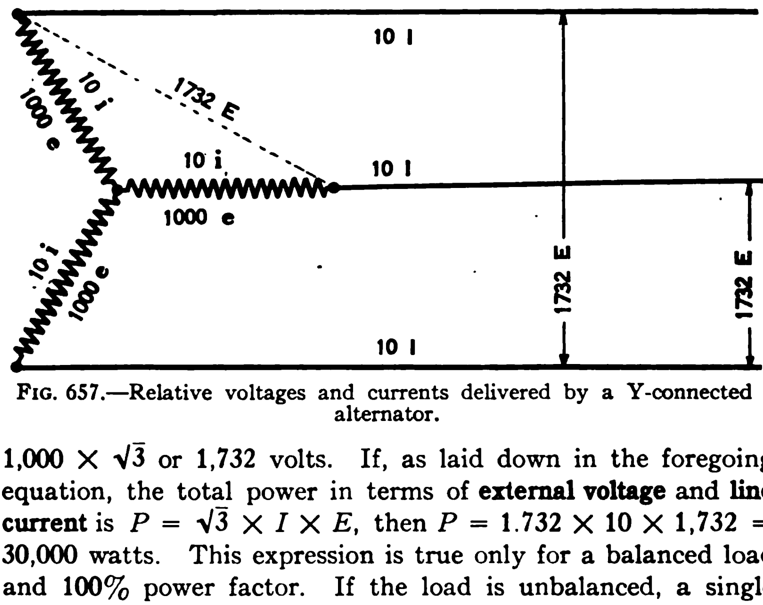


FIG. 657.—Relative voltages and currents delivered by a Y-connected alternator.

1,000 × $\sqrt{3}$ or 1,732 volts. If, as laid down in the foregoing equation, the total power in terms of **external voltage** and **line current** is $P = \sqrt{3} \times I \times E$, then $P = 1.732 \times 10 \times 1{,}732 =$ 30,000 watts. This expression is true only for a balanced load and 100% power factor. If the load is unbalanced, a single expression such as the foregoing would not represent the facts. If the load is balanced and the power factor anything less than 100%, the expression would be $P = \sqrt{3} \times I \times E \times \cos \Phi$.

The equations **for a Δ-connected machine** with a 100% power factor are as follows:

$$I = i \times \sqrt{3} \quad (1) \qquad e = E \quad (3)$$

$$i = \frac{I}{\sqrt{3}} \quad (2) \qquad p = e \times i \quad (4)$$

$$p = E \times i \quad (5)$$

$$P = 3 \times p = 3 \times \frac{I \times E}{\sqrt{3}} = \frac{\overset{\sqrt{3}}{\cancel{3}} \times I \times E}{\cancel{\sqrt{3}}} \quad (2 \text{ and } 5)$$

$$P = \sqrt{3} \times I \times E \quad (6)$$

It will be seen from the foregoing that the equation for the total power is the same when a machine is Δ connected as when the same machine is Y connected. With a Y connection the $\sqrt{3}$ is a **factor** of the **line voltage,** Fig. 657. With a Δ connection the $\sqrt{3}$ is a **factor** of the **line current.** Thus, when Δ connected,

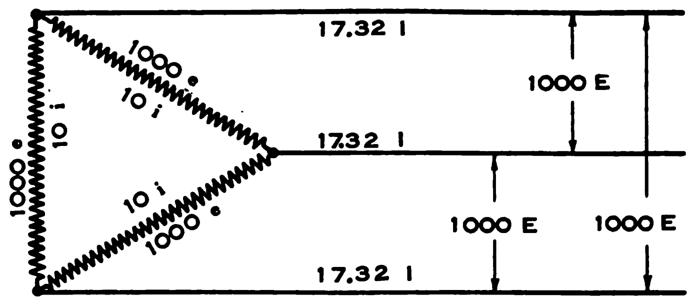


FIG. 658.—Relative voltages and currents delivered by a Δ connected alternator.

as in Fig. 658, $P = \sqrt{3} \times I \times E = 1.732 \times 17.32 \times 1000 = 30{,}000$ watts. This is the same power which the machine delivered when Y connected except that in the Y connection the current was 10 amperes and the e.m.f. was 1,732 volts while in the Δ connection the current is 17.32 amperes and the e.m.f. is 1,000 volts. These expressions are likewise based upon balanced load and 100% power factor. For unbalanced load the above

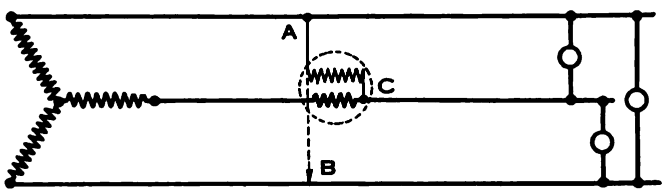


FIG. 659.—Measurement of power in a three-phase circuit by one wattmeter.

expression would not represent the facts, and if the power factor was less than 100%, the power would be, $P = \times \sqrt{3}\ E \times I \times \cos \Phi$.

The power in a three-phase system can be measured by one, two or three wattmeters. Fig. 659 shows the connections for measuring the power with one wattmeter. Here the current coil is connected in the wire C, which also carries one end of the

potential coil. The other end of the potential coil is connected first to A and then to B. With a load that is fairly well balanced and the power factor 100% the sum of the two readings equals the total power as in the case of a two-phase measurement. If the power factor is low, the connections to the potential coil in lines B and C should be reversed and the difference between the two readings taken as the total power instead of the sum. This method is approximately correct when the system is fairly well balanced.

Fig. 660 shows the two-wattmeter method. Here the current coil of one wattmeter is connected in the line A, to which one end of the potential coil is likewise connected. The current coil of the other wattmeter is connected to the line B, to which one end of the potential coil is likewise connected. The remaining ends of the two potential coils are connected to the wire C, which contains no current coil. The sum of the two-wattmeter readings accurately indicates the total power in the system whether the load is balanced or not. At power factors below 50% one instrument will read backwards. In this case its potential connections could be reversed, which will make it read forward. The difference in the two readings instead of their sum should then be taken as the correct power. The use of two wattmeters is the method most generally employed for measuring three-phase power.

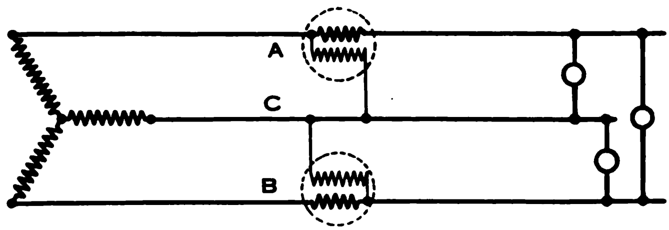


FIG. 660.—Measurement of power in a three-phase circuit by two wattmeters.

The total power in a three-phase system may be measured by three wattmeters, provided the middle point of the Y connection of the alternator is available. If, however, this point is not accessible, or the alternator is Δ connected, an artificial neutral may be obtained by connecting three non-inductive resistances in Y, and connecting their outside ends across the three lines

A, B and C, as shown in Fig. 661. One end of a potential winding and the series winding of each of the three wattmeters are connected in each of the line wires A, B and C, as shown. The remaining ends of the potential windings are connected to the

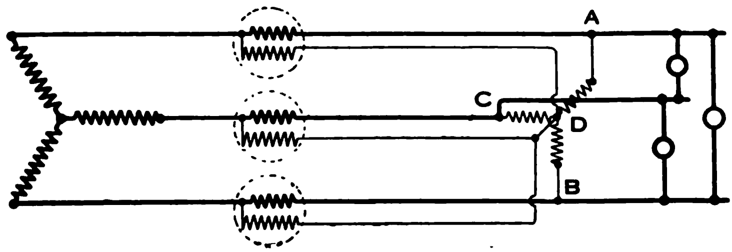


FIG. 661.—Measurement of power in a three-phase circuit by three wattmeters.

middle point of the artificial neutral. The sum of the three wattmeter readings is now taken to represent the true power. The resistances, D, must not be low enough to disturb the line potential by drawing an appreciable current therefrom, and yet they must be negligibly small when compared with the resistance of the potential coils in the wattmeters.

Single-Phase Rating of Polyphase Machines

It has been generally stated that the single-phase rating of a three-phase machine is 70.7% of its three-phase rating. This

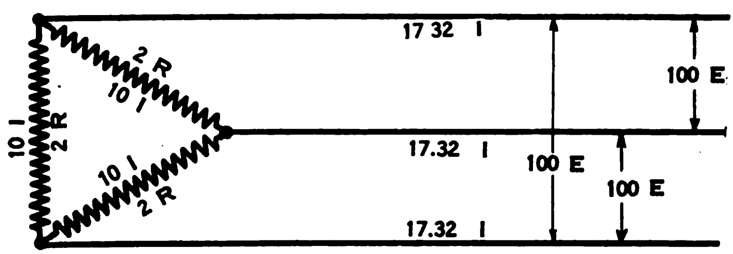


FIG. 662.—Distribution of current and voltages in a three-phase machine.

is based upon equal heating effects and, while not always true, it may be true in small machines with natural ventilation. The proof is as follows:

Consider a three-phase machine, Fig. 662, having a resistance of 2 ohms in each phase and absorbing a current of 10 amperes in each phase under a line pressure of 100 volts. The current passing through the line, if the machine is Δ connected, will thus

be 17.32 amperes per wire and the potential difference between each pair of wires 100 volts. The power which the machine absorbs three phase will be $P = \sqrt{3} \times I \times E = 1.732 \times 100 \times 17.32 = 3{,}000$ watts. The power lost in the windings due to heating will be I^2R per phase multiplied by 3 for a three-phase machine. Thus $10^2 \times 2 = 200$ watts per phase. Multiplying this by the number of phases, 3, gives 600 total watts loss.

The output of a direct-current machine is limited by two factors, heating and sparking. As there are no brushes to spark on an alternating-current machine, its output is limited solely

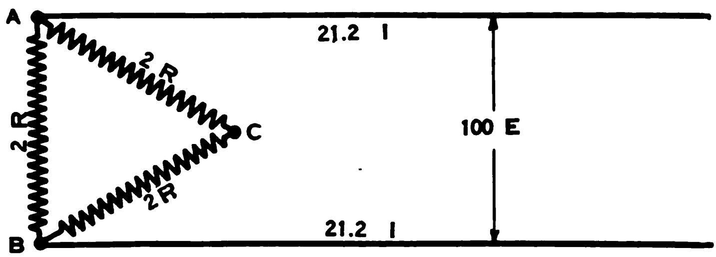


FIG. 663.—Distribution of current and voltages in a three-phase machine when operated on a single-phase circuit.

by its heating effect. This same machine will be loaded to the limit of its output when the same 600 watts are lost in heating on a single-phase circuit. When connected single phase the two line wires will come to the points A-B, Fig. 663, while the point C will not be directly connected to the external circuit. As each phase has a resistance of 2 ohms, the connections as shown consist of 2 ohms across A-B and $2 + 2 = 4$ ohms across A-C-B. The combined resistance is equal to the product divided by the sum of the resistances in these two paths;

$$\text{thus } \frac{2 \times 4}{2 + 4} = 1.333 \text{ ohms.}$$

As $I^2R = P$, the current required to bring about a given loss will be

$$I = \sqrt{\frac{P}{R}}.$$

The permissible loss is 600 watts. Therefore

$$\sqrt{\frac{600}{1.333}} = 450 = 21.2 \text{ amperes.}$$

Based on the same voltage of transmission, the machine may now receive 21.2 amperes times 100 volts or 2,120 watts intake single phase.

$$\frac{2120\ P\ \text{single phase}}{3000\ P\ \text{three phase}} = 70.7\%.$$

Thus the single-phase capacity of the machine for the same heating effect is 70.7% of its three-phase capacity. In actual operation the single phase rating is usually much less than 70.7% of the three-phase capacity due to local heating, etc. In extreme cases it may be as low as 30%.

Power Lost in Three-Phase Transmission

It has already been pointed out that the copper required for transmitting a given amount of power, a stated distance at a

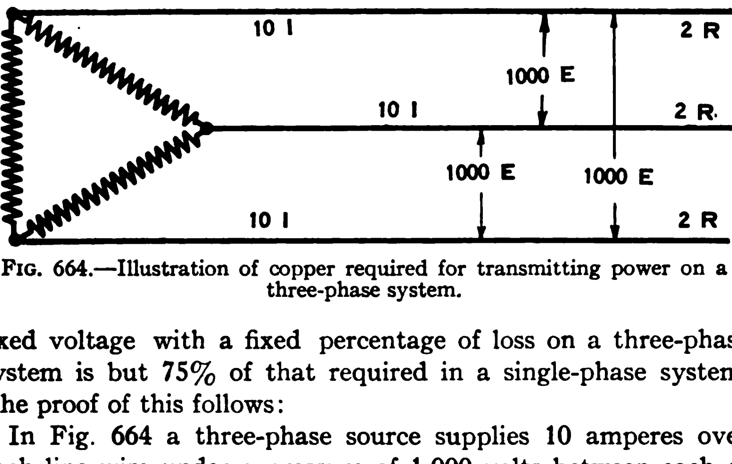


FIG. 664.—Illustration of copper required for transmitting power on a three-phase system.

fixed voltage with a fixed percentage of loss on a three-phase system is but 75% of that required in a single-phase system. The proof of this follows:

In Fig. 664 a three-phase source supplies 10 amperes over each line wire under a pressure of 1,000 volts between each of the two line wires. The total resistance of each line wire is assumed to be 2 ohms. The power lost in each line wire will be $I^2R = P = 10^2 \times 2 = 200$ watts. As there are three line wires the total loss will be $200 \times 3 = 600$ watts. The power transmitted is $P = I \times E \times \sqrt{3} = 10 \times 1{,}000 \times 1.732 = 17{,}320$ watts. To transmit the same power at the same voltage single phase will require $\frac{P}{E} = I = \frac{17{,}320}{1{,}000} = 17.32$ amperes. Thus in Fig. 665 the pressure will be 1,000 volts, and the current in each of the two line wires will be 17.32 amperes. As the same total loss must be involved in the system to make it comparable with the

three-phase system the 600 watts previously lost will be divided between two wires; thus $\frac{600}{2} = 300$ watts per wire. The resistance for each of these wires, in order that they shall have 300 watts loss therein, will be $I^2R = P$, therefore

$$\frac{P}{I^2} = R = \frac{300}{17.32^2} = 1 \text{ ohm.}$$

Thus, if each of the two line wires in Fig. 665 has a resistance of 1 ohm, there will be the same total power lost with the same

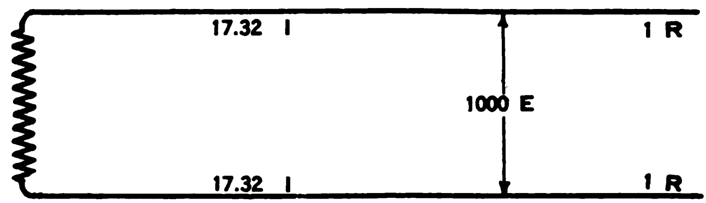


FIG. 665.—Illustration of copper required for transmitting power on a single-phase system.

total power transmitted as in Fig. 664, when the resistance of each line wire was 2 ohms. Now each wire of a single-phase line, in order that it may possess one-half the resistance, must be twice the cross-section of each wire of the three-phase line. If one of the single-phase wires weighs 50 pounds, then the two will weigh 100 pounds. If one wire of the three-phase system weighs 25 pounds, then the three wires will weigh 75 pounds.

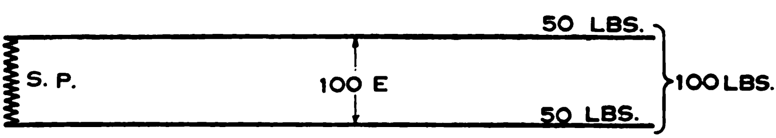


FIG. 666.—Total copper required for a single-phase transmission.

Thus the three-phase system required 75% of the copper required on the single-phase system for transmitting the same power at the same voltage the same distance with the same loss.

The following is an illustration of the economy of copper effected in a three-phase four-wire system.

It has been previously stated that the economy of copper in a transmission line varies as the square of the e.m.f. applied.

Thus, if 100 volts be employed in one case and 173 volts in another case, the copper required will be inversely proportional to the square of these two potentials. Now 173 volts squared equals 30,000 volts while 100 squared equals 10,000. As 30,000 is three times 10,000 or a ratio of three to one, the copper required to transmit a given power the same distance with a fixed loss will be in the ratio of one to three for voltages of 173 and 100 respectively.

As previously stated, the copper required in a three-phase three-wire transmission is 75% of that required in a two-phase four-wire transmission for the same e.m.f. Thus, if the voltage at the lamps in Fig. 668 is 100, and the weight of each of the three wires is 25 pounds, then the total copper required will be

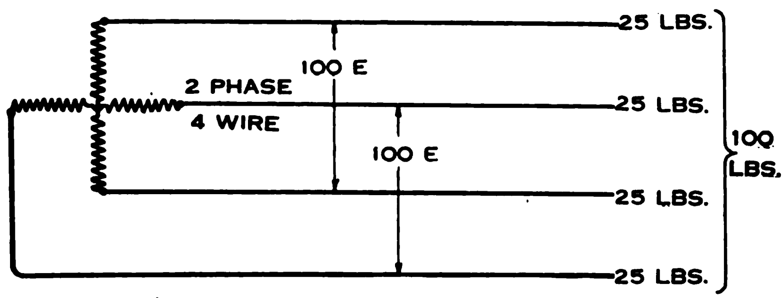


FIG. 667.—Total copper required for a two-phase, four-wire transmission.

75 pounds. Now if a three-phase four-wire system be employed as in Fig. 669, the voltage of transmission will be 173 volts in order that it may be possible to deliver 100 volts at the lamps, for the load is connected in this case between each of the principal wires and the neutral, and across these there is impressed but the voltage of one phase, which in this case will be 100. But the voltage across any two of the principal line wires is the geometric sum of two phases in series or 173 volts. Thus, while the power is utilized at 100 volts, it is transmitted at 173 volts. As has just been pointed out, the relative copper required for 173 volts will be one-third of that required for 100 volts. Hence each of the transmitting wires will weigh 8⅓ pounds as against 25 pounds for each of the three wires in Fig. 668. To this must be added the weight of the neutral wire. In transmission systems it is customary to make the size of the neutral one-half

that of the outside wires. This would make the weight $4\frac{1}{6}$ pounds; the sum total of the four wires would then be 29.2 pounds.

The relative amounts of copper in the principal systems in use are shown in Figs. 666, 667, 668 and 669. They represent the transmission of equal amounts of power the same distance

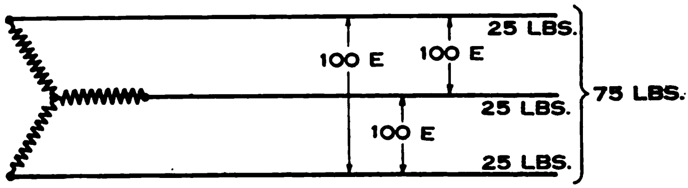


FIG. 668.—Total copper required for a three-phase, three-wire transmission.

with the same percentage of loss and with the same voltage at the lamps or motors in each instance. The single-phase system is the simplest, but the maximum output of the alternator for a given amount of copper and iron is not realized. Furthermore, it is not possible to automatically start a certain type of induction motor on this system. The other extreme is represented in Fig. 669, where a great economy of copper is

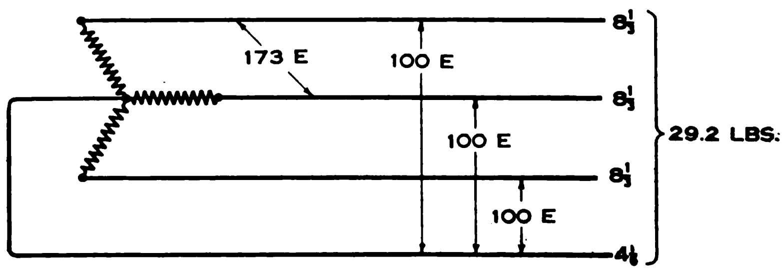


FIG. 669.—Total copper required for a three-phase, four-wire transmission.

effected, but the introduction of the fourth wire into the distributing network is a serious complication. Between these, the three-wire three-phase system represented in Fig. 668 is probably the most desirable. It includes three distinct advantages:

First, that of realizing the maximum output for a given amount of iron and copper in the alternator.

Second, the ability to start induction motors automatically.

Third, an inherent economy in copper.

Hence this is the most widely used system of transmitting power today.

Phase Relations in Three-Phase Circuits

The line e.m.fs. in either a Y or Δ connected three-phase system are always 60° apart in electrical phase (that is, in direction). The line currents are 120° apart in both electrical and time phase. Thus Δ voltage relation and Y current relation is obtained between the line e.m.fs. and the line currents in any three-phase system regardless of whether the alternator is Y or Δ connected.

Fig. 670 shows a Y connection. Here the current in I_1 is 120° in phase from the current in I_2, and the current in I_2

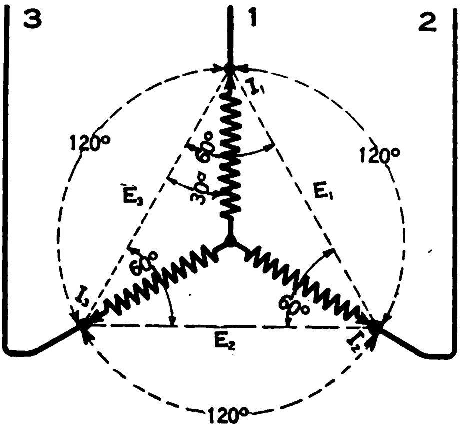


FIG. 670.—Relation between phase voltages and currents, and line voltages and currents in a Y-connected machine.

is in turn 120° in phase from the current in I_3. But the voltage measured by a voltmeter between line wires 1 and 2 or E_1 is but 60° in phase from the voltage E_2 between line wires 2 and 3. This is because the voltage measured across the line wires is not the separate phase voltage in any case but a resultant of two phases in series. This resultant is 30° behind the current in one phase and 30° ahead of the current in the other phase. Thus, while the currents follow each other in line wires 1, 2 and 3, 120° apart, the measured voltage between line wires 1—2, 2—3, and 3—1, which in each case are resultants of two separate phases, are 60° apart.

This is equally true for a Δ connection, shown in Fig. 671. Here the current in line 1, or I_1, is a resultant of two currents i_1 and i_3, 60° apart in phase. The resultant current in the line wire is 30° out of phase with each of the components. Likewise the current in line wire 2, or I_2, is the sum of the currents i_1 and i_2, while the current in line 3, or I_3, is the sum of the currents i_2 and i_3. The resultant currents I_1, I_2 and I_3 are thus 120° apart in phase, while the separate phase voltages E_1, E_2 and E_3 are 60° apart due to the connections.

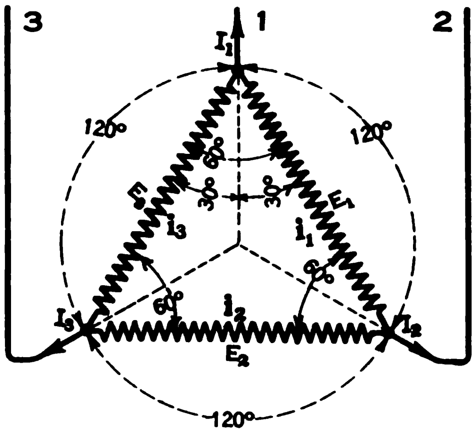


FIG. 671.—Relation between phase voltages and currents, and line voltages and currents in a Δ-connected machine.

Measurement of Power in Three-Phase Systems

It has previously been stated that the total power in a three-phase system could be measured by 2 wattmeters. This is true whether the load is balanced or unbalanced, and whether the power factor is unity or a fraction thereof.

With a balanced load and a power factor of 100% the total power of a three-phase circuit is $P = \sqrt{3} \times E \times I$.

E = voltage between any two-line wires.
I = current in one-line wire.

Expressing the total power in terms of phase power:

$P = 3 \times e \times i$.

Where e = voltage of one phase.
i = current in one phase.

In Fig. 672 the current in the current coil of wattmeter W_1 is in phase with the e.m.f. of the phase O-B of the alternator with which it is connected, but the e.m.f. applied to the potential

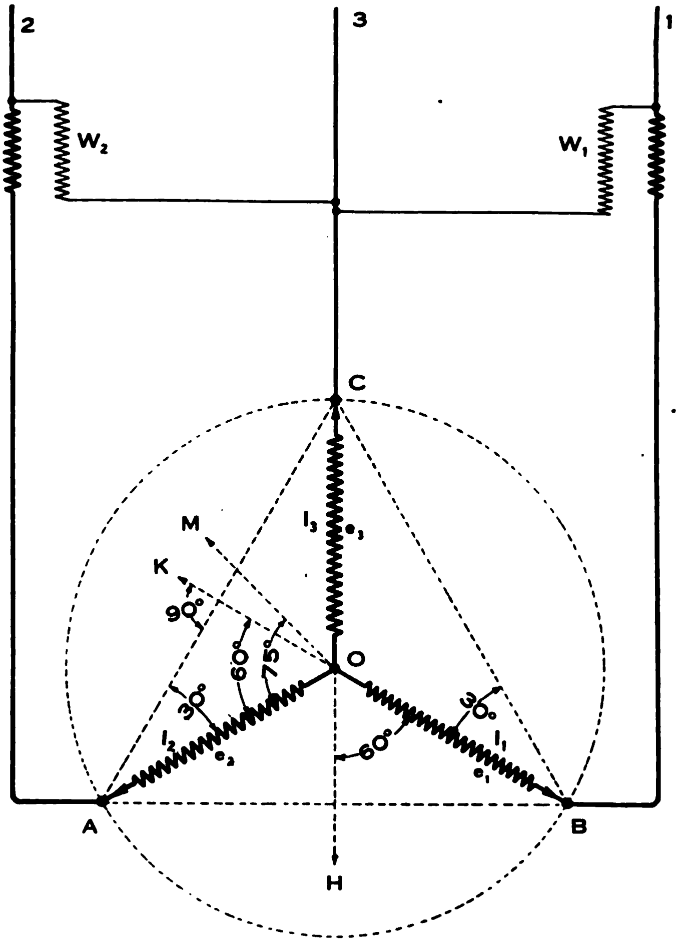


FIG. 672.—Result of various power factors upon power registered by each of two wattmeters in three-phase circuit.

coil of this wattmeter is 1.732 times the e.m.f. of one phase of the alternator and, moreover, out of phase with the current in the series coil of the wattmeter by 30°. This is equally true for wattmeter W_2 with respect to phase O-A of the alternator.

The power, p, indicated by one wattmeter will be

$$E \times I \times \cos 30° \quad \text{or} \quad E \times I \times 0.866.$$

$$\text{Since } E = e \times 1.732 \quad \text{and} \quad i = I,$$

$$p = e \times 1.732 \times i \times 0.866 \quad \text{or} \quad p = e \times i \times 1.5.$$

As the total power in the circuit is represented by the equation $P = e \times i \times 3.0$, it is evident that each wattmeter reads one-half the total power in the circuit. Then

$$\frac{e \times I \times 1.5}{e \times I \times 3} = \frac{P \text{ on one wattmeter}}{\text{Total power}} = \tfrac{1}{2} \text{ of the total power}$$

registered by each wattmeter. As each meter registers one-half of the total power, then the two meters will register the entire power in the circuit.

If the alternator is Y connected, 1.732 is a factor of e. If Δ connected, it is a factor of i The formula is equally true no matter how the source is connected.

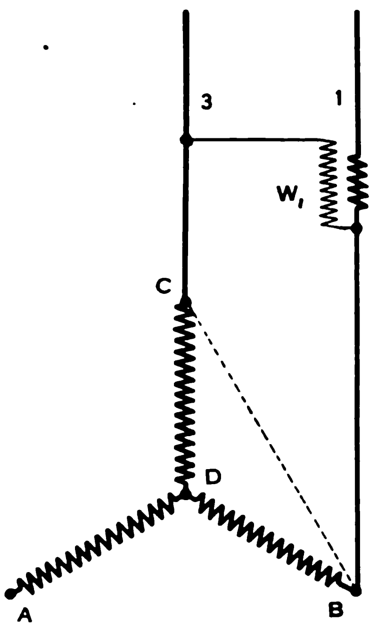


Fig. 673.—One wattmeter registers entire power when load is wholly upon one phase.

If the load is badly unbalanced as in Fig. 673, the currents in phases *D-B* and *D-C* merge into one resultant which is in phase with the e.m.f. across *B-C*. Thus if the load is wholly connected across line wires 1 and 3, and the circuit for *A* is opened, wattmeter W_2 will register zero and wattmeter W_1 will register all the power. The elimination of wire 2 reduces the system to a single-phase circuit. The entire current is in phase with the e.m.f. if the power factor of the load is 100%. If, with the most extreme condition of unbalance as here illustrated with wattmeter W_2 registering zero and wattmeter W_1 registering total power, the sum of the readings represents the

total load, and if with a practically balanced load the two wattmeters register the total power, then it will be true that the sum of the readings of the two wattmeters will show the total power for each and every condition of balanced or unbalanced load.

When the power factor falls to 50% in a three-phase three-wire system where two wattmeters are used to register the power, the readings of one wattmeter will drop to zero while the other registers the total power.

To understand this, assume the currents in each phase of the alternator to be in phase with the voltage of that particular winding in which the current flows when the power factor is 100%. Thus, in Fig. 672, I_1 is in phase with e_1; I_2 is in phase with e_2; I_3 is in phase with e_3. The e.m.f. B-C, across the line wires 1 and 3 impressed upon the wattmeter W_1, is out of phase with both I_1 and I_3 by 30°. This is also true of the e.m.f. A-C, across line wires 2 and 3, with respect to I_2 and I_3.

If, now, an inductive load causes the currents in line wires 1, 2 and 3 to lag 60° behind their respective voltages which means a power factor of 50%, the phase direction of current I_1, which was O-B, will be O-H, and I_2 swings from O-A to O-K. This latter current is squarely at right angles to the e.m.f. across A-C, and wattmeter W_2 therefore registers zero. W_1 therefore registers all the power and the voltage C-B on its potential coil and the current O-H in its series coil are in the same general direction.

If the angle of lag increases still further, W_1 still continues to register in a positive direction, and in fact it can never reverse, for the direction O-H will always be more or less in the same general direction as C-B; but as the angle of lag increases, the current in O-A swings in phase beyond the point O-K, to the position O-M, where it will be in opposition to the voltage across A-C. Before the current lagged at all, I_2 or O-A was in the same general direction as the e.m.f. C-A, but the great angle of lag indicated when the direction is O-M causes I_2 to oppose the voltage C-A, and the torque between the current and potential coils of the wattmeter W_2 reverses. This will cause W_2 to indicate backwards. If W_2 is an indicating wattmeter, it cannot indicate backwards. To obtain an indication it will be necessary to reverse the terminals of either the current or the potential coil

with respect to lines 2 and 3. This will cause it to indicate in a positive direction, but the readings now obtained must be deducted from the indication of W_1 to get the true power in the system.

The particular meter, W_2 or W_1, which will indicate backward when the power factor is below 50% depends upon the direction of **phase rotation.** If in Fig. 672 the current in line wire 1 reaches its maximum in a positive direction first, then in line 3 and then in line 2, the direction of phase rotation is counter-clockwise. Meter W_2 will now be the one to reverse. If, however, the direction of phase rotation be reversed, then W_1 would be the meter to indicate backward. This could be brought about by crossing the connections between any two of the alternator leads and the two corresponding line wires. The same result would be accomplished if the alternator were rotated backwards.

If W_1 and W_2 were integrating wattmeters and no reversal of connections took place, it is evident that W_2 would run backward when the power factor fell below 50%. It would thus subtract from the registration of W_1 so that the combined registrations of the two meters should be the correct power in any case. But as these meters are **compensated** for rotation in a forward direction, the reversed registration of W_2 would not be accurate.

A polyphase wattmeter consists of two single-phase elements operating upon the same shaft and recording on the dials through one gear train. When the power factor is below 50% one of these elements **tends** to rotate the shaft in a backward direction and thus retards the forward rotation due to the other element. This reduces the total registration by the correct amount, so that the **dial readings will be the true power** for every condition of power factor.

SECTION XIV CHAPTER IX

ALTERNATING CURRENT

POWER IN POLYPHASE SYSTEM

1. Give formula for the power in a three-phase alternating current circuit, at various power factors.

2. Give formula for the e.m.f. in a two-phase three-wire system. If the current in each outside wire of a two-phase system is 14 amperes, what is the

current in the middle wire? If the voltage in each phase of a two-phase system is 1,100, what is the voltage between the two outside wires?

3. In what two ways may the power in a two-phase three-wire system be measured? Give sketch.

4. Give formula for the power in a three-phase, Δ-connected alternator at any power factor.

5. Give formula for the power in a Y-connected alternator for any power factor.

6. Each phase of a Y-connected alternator furnishes 2,200 volts and 15 amperes. What will be the current in each line wire and the difference in potential between any two line wires in the external circuits of this machine? What is the total power delivered?

7. Each phase of a Δ-connected alternator furnishes 6,600 volts and 12 amperes. What is the current in each line wire and the difference in potential between any two line wires in the external circuits of this machine? What is the total power delivered?

8. In what three ways may the power in a three-wire system be measured? Give sketches.

9. What is the theoretical capacity of a three-phase machine operated single phase? Is this capacity fully realized? Why?

10. Explain why a three-phase three-wire system requires but 75% of the copper required by a single-phase system with the same voltage of transmission.

11. In a three-phase system, operating under 100 per cent power factor:

(*a*) What is the phase relation of the current in the three line wires?

(*b*) What is the phase relation of the voltages between one pair of wires and another pair?

(*c*) What is the phase relation between the current in one wire and the voltage between that wire and either of the other two?

12. When two wattmeters are used to measure the power on a three-phase circuit, explain how one wattmeter measures $1\frac{1}{2}$ times the power delivered by a single phase of that machine. (Balanced load, 100% power factor.)

13. What percentage of the total power delivered by a three-phase machine operating with unity power factor and balanced load, is supplied by one phase?

14. If a three-phase system is delivering power from one phase only, sketch and explain how one wattmeter may correctly measure the total power delivered?

15. When two wattmeters are used to measure the total power in a three-phase system (100% power factor) what is the phase relation between the current and voltage in each meter? Why is this so?

16. If the current is caused to lag, what will be the effect upon the phase relations of the current and voltages in the two meters referred to in Question 15?

17. What will be the effect upon the power registered by each meter in Question 16 as compared with the power registered in Question 15?

18. To what extent must the current lag in the external circuit to cause the entire power of a three-phase system to be registered by one wattmeter? Why is this so?

19. Under what conditions will one of the two wattmeters on a three-phase system indicate backward? Under these circumstances how can the true power be obtained?

20. A three-phase alternator delivers 10 amperes to each line wire and maintains 6,600 volts between each pair of line wires. The power factor of the system is 86.6%. Determine:

(*a*) The total power delivered by the machine.

(*b*) The current and e.m.f. of each phase winding; when connected in Δ.

(*c*) The current and e.m.f. of each phase winding, when connected in Y.

(*d*) Sketch a circuit with 2 wattmeters so connected that they will measure the total power in the system under any power factor.

(*e*) If recording meters set at zero to start, are employed, what will be the reading of each meter at the end of five hours' time, if the power factor, as above, is 86.6%?

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